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Byproducts from Dairy Processing

Diana Oliveira^{1,2}, Patrick Fox¹, and James A.O'Mahony^{1,2}

¹ School of Food and Nutritional Sciences, University College Cork, Room 234, Food Science Building, Cork, Ireland

² Dairy Processing Technology Centre, University College Cork, Room 234, Food Science Building, Cork, Ireland

4.1 Introduction

More than 6 billion people worldwide consume milk and milk products. While the majority of these people live in developing countries, milk and dairy products are major components of the diet in Europe, North and South America, Australia, New Zealand and some Middle Eastern countries. In the last three decades, global milk production has increased by more than 50%, from 500 million tonnes in 1983, to 769 million tonnes in 2013 and about 800 million tonnes in 2015, of which 163, 46, 105, and 31 million tonnes were produced in the European Union, Eastern Europe, North America and Oceania, respectively. World milk production is projected to increase by 177 million tonnes (23%) by 2025, compared to the average production in the base years 2013–2015, and a general expansion in dairy trade is expected over the coming decade (Figure 4.1). The annual growth rate differs for individual dairy products: butter (2.3%), cheese (2.1%), skimmed milk powder (SMP; 2.2%) and whole milk powder (WMP; 1.8%) (OECD-FAO 2016). An overview of the utilization of milk and dairy products in Europe is provided in (Figure 4.2).

Because milk is perishable and its production was, traditionally, seasonal, milk surplus to immediate requirements was converted to more stable products, with some examples being butter or ghee, fermented milk and cheese; smaller amounts of dried milk products were traditionally produced by sun-drying; such products are still important and many new variants thereof have been introduced (Table 4.1). Since the publication of the book *Byproducts from Milk* (Whittier and Webb 1950), enormous developments have taken place in the dairy industry. At that time, the dairy industry was dominated by butter, cheese, liquid milk, and cream. The byproducts were generally used as liquid animal feed or applied to the land as fertilizer. The gradual switch from traditional products to convenience foods posed a new challenge for the food industry, while several new categories of dairy products have been developed during the past 150 years, e.g. sweetened

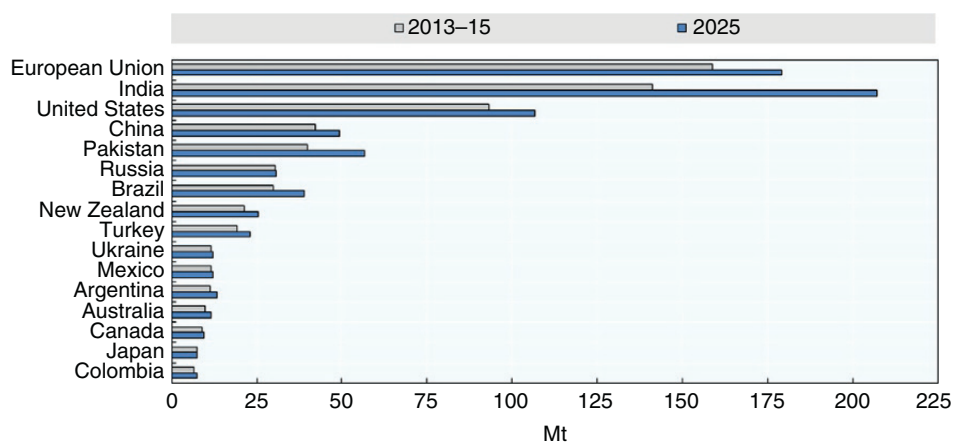


Figure 4.1 Milk production for major countries and regions. *Source:* From: OECD-FAO (2016).

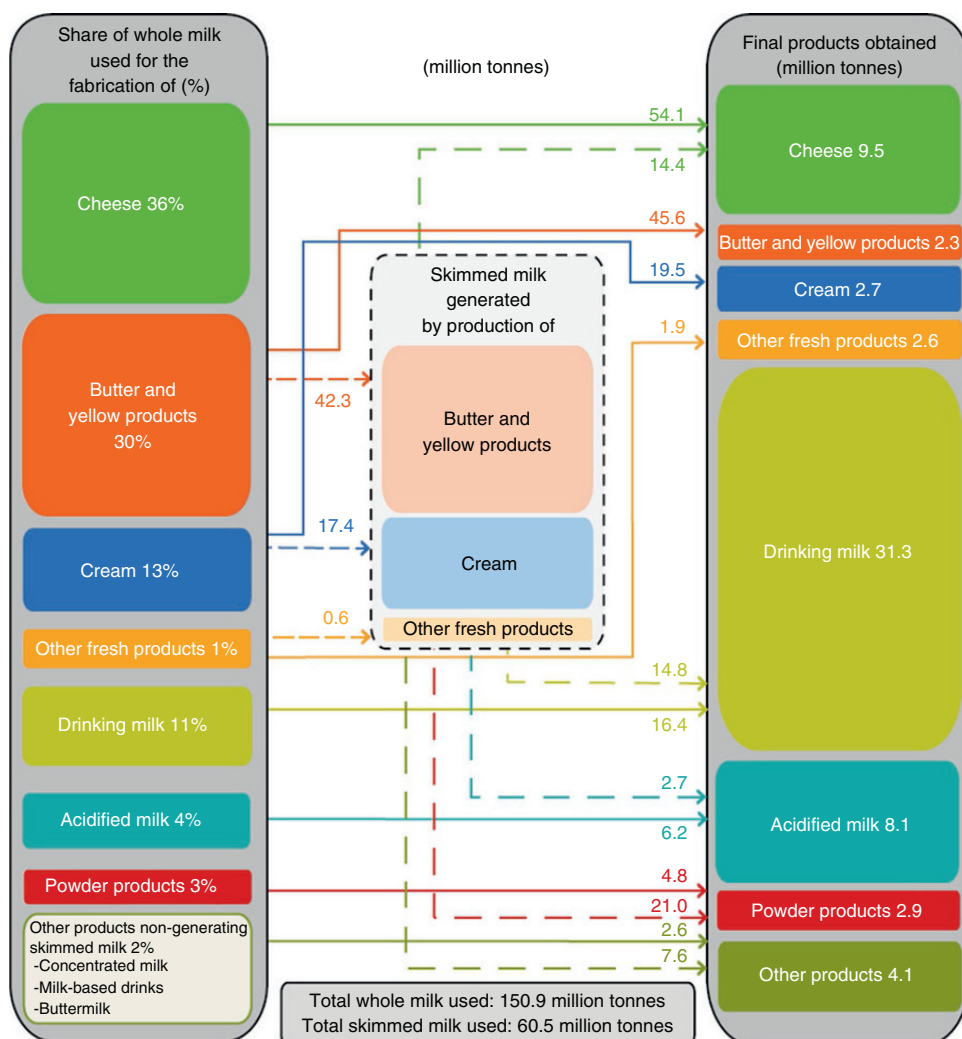


Figure 4.2 Utilization of milk and dairy products in Europe in 2015 (% and million tonnes). *Source:* From (Eurostat 2016).

Table 4.1 Diversity of dairy products.

Process	Primary Product	Further Products
Centrifugal separation	Cream	Butter, butter oil, ghee, anhydrous milk fat; creams of various fat content (coffee creams, whipping creams, dessert creams; cream cheeses)
	Skim milk	Powders, casein, cheese, protein concentrates and infant formulae
Thermal processing		HTST or super-pasteurization, UHT-sterilized or in-container sterilized
Concentration, thermal evaporation or membrane filtration		Evaporated or sweetened condensed milk
Concentration and drying		Whole milk powders; infant formulae; dietary products
Enzymatic coagulation	Cheese	1000 varieties; further products, e.g. processed cheese, cheese sauces, cheese dips
	Rennet casein	Cheese analogues
	Whey	Whey powders, demineralized whey powders, whey protein concentrates, whey protein isolates, individual whey proteins, whey protein hydrolysates, nutraceuticals. Lactose and lactose derivatives
Acid coagulation	Cheese	Fresh cheeses and cheese-based products
	Acid casein	Functional applications, e.g. coffee creamers, meat extenders; nutritional applications, cream liquors
Fermentation		Various fermented milk products, e.g. yogurt, buttermilk, acidophilus milk, bio-yogurt
Freezing		Ice-cream (numerous types and formulations)
Miscellaneous		Chocolate products

Source: From: Fox and McSweeney (1998).

condensed milk, in-container sterilized milk, a range of milk powders, ultra-high temperature (UHT)-sterilized milk, ice creams, infant foods, milk protein products, lactose and lactose derivatives.

One of the important developments in dairy technology in more recent years has been the fractionation of milk into its principal constituents, lactose, milk fat fractions, minerals and milk proteins, with the latter serving as the means by which dairy protein-enriched/isolated ingredients are made available; examples include caseins, caseinates, milk protein concentrates (MPCs), milk casein concentrates (MCCs), whey protein concentrates (WPCs), whey protein isolates (WPIs), mainly for use as functional and nutritional protein ingredients, while more recently, some milk protein ingredients, such as lactoferrin, lactoperoxidase, and immunoglobulins have been developed and are marketed as “nutraceuticals,” i.e. proteins for specific physiological/nutritional functions.

As a raw material, milk has many attractive features:

- Milk was designed for animal nutrition, and hence, contains the necessary nutrients in easily digestible forms (although the balance is designed for the young of a particular species) and free of toxins.
- The principal constituents of milk (lipids, proteins, and carbohydrates) can be fractionated readily and purified using relatively simple approaches, for use as food ingredients.
- Milk is readily converted into products with highly desirable organoleptic and physical characteristics and its constituents have many desirable, and some unique, physico-chemical functionalities (e.g. gelation and interfacial properties).
- The modern dairy cow is a very efficient convertor of plant material, and over the last 100 years, the productivity of dairy cattle has risen considerably due to scientific advances in many key enabling areas, such as milking equipment, reproductive technologies, nutrition, management, and genetics.
- In terms of the quantity of protein that can be produced per hectare, milk production, is much more efficient than meat production but less efficient than some plants (e.g. soy beans). However, the functional and nutritional properties of milk proteins are superior to those of plant proteins, and since cattle (in particular, sheep and goats) can thrive under farming conditions not suitable for growing cereals or other plants, dairy animals need not be competitors with humans for the use of land.
- One of the limitations of milk as a raw material is its perishability, due to the fact that it is an excellent source of nutrients for microorganisms as well as for humans. However, this perishability is readily overcome by a well-organized, efficient dairy industry.

Milk is probably the most adaptable and flexible of all food materials, as is apparent from Table 4.1, which shows the principal families of milk-based foods – some of these families contain several hundred different products. As the composition, and the quantity, of these primary products usually do not match those of raw milk, this gives rise to byproducts which must be processed. A key objective in processing and fractionating milk into commercially viable, nutritional and techno-functional ingredients and products is to minimize side stream and waste generation. In the dairy sector, given the volume, composition, and chemical/biological oxygen demand of side-streams and byproducts, these must be processed even if they have a negative value (Boer 2014). A byproduct is a secondary product derived from a manufacturing process or chemical reaction. In the context of production, a byproduct is the “output from a joint production process that is minor in quantity and/or net realizable value compared to the main products.” A byproduct can be useful and marketable or it can be considered waste, depending on several factors, including composition, volume, quality and ease of processing. Today, several thousand different product types are produced from milk; these fall into the following principal groups: liquid/beverage milk (40%), cheese (35%), milk powders (15%), concentrated milks (2%), fermented milks (2%), butter (30%, some of which is produced from cream obtained as a byproduct in the manufacture of other products), ice cream, infant formula, cream-based products, protein-rich products and lactose (O’Mahony and Fox 2014).

In the processing of milk, what might be considered a byproduct is arbitrary in some cases, e.g. in the manufacture of butter or butter oil, buttermilk and butter serum are clearly byproducts, whereas, in the separation of milk, either the cream or the skimmed

milk could be the byproduct, depending on the objective of the process; in this article, cream and skimmed milk are considered as byproducts. In the manufacture of butter, butter is clearly the primary product and buttermilk is a byproduct; likewise, in the manufacture of cheese from whole or skimmed milk, cheese is clearly the primary product and whey is a byproduct. Cream is used to produce a range of dairy products such as butter, butter oil, ghee, anhydrous milk fat (AMF), sour cream and cream cheese. As these are products as such, they will not be considered in more detail here, but have been the subject of several relevant publications, namely, Wilbey (2009), Smiddy et al. (2009), Guinee and Hickey (2009), Illingworth et al. (2009) and Mortensen (2009, 2011).

4.2 Skimmed Milk-Based Byproducts

4.2.1 Skim Milk

Skim milk is a co-product obtained during the manufacture of cream. Skim milk is rich in non-fat solids (i.e. lactose and protein) and has good nutritional value. Skim milk is regarded as a byproduct only when it is not economically used or further processed to derive byproducts like casein and related products, co-precipitates, protein hydrolysates, etc. Skim milk may be pasteurized and sold as a fluid milk product, used in the formulation of infant nutritional products (usually as skim milk concentrate), concentrated and filled with vegetable oils in the production of fat-filled and enriched milk products and is used in standardization of protein content for the manufacture of other dairy products (e.g. cheese) or it may be preserved in a dried powder format. Dried skim milk powder (SMP) is normally produced using spray drying technology, but may be produced by roller drying; SMP has many applications, including, but not limited to, infant nutritional products, recombined milk products, bakery, confectionery and ice cream.

4.2.2 Cheese and Fermented Skim Milk Products

Two major families of acid-coagulated cheese are produced from skimmed milk: Cottage cheese and Quarg. A cheese called “Cottage” is produced in many countries but the term usually refers to that which originated in the United States, but is now produced widely. The washed cheese curd is usually dressed with cream to improve its flavor; the typical composition of such a product is 79% moisture, 14% protein, 4% fat and 1% salt. It is particulate and is consumed mainly in salads. American-type Cottage cheese was described by Farkye (2004). The second family is Quarg (Quark) and Quarg-like cheeses, including Bakers cheese, Tvorog, Fromage Frais, Labneh, Petit Suisse, Neutchatel, Skyr, and Queso Blanco. In the production of such products, the curds are generally cooled, optionally blended with cream and/or condiments and packed. In such manufacturing processes, the whey proteins (WPs) are generally lost in the whey, but various modifications (e.g. Centri-whey, Lactal, and Thermo processes) have been developed and implemented to recover the WPs, thereby reducing substantially the generation of a further byproduct stream, while increasing yield of the primary cheese product. In the Centri-whey process, the whey is heated to denature the WPs, which are recovered by centrifugation and added back to the cheese milk. In the Lactal process, the heat-precipitated WPs are allowed to settle and the supernatant decanted; the precipitated

protein is further concentrated by centrifugation and added to regular Quarg to give about 20% protein. In the Westfalia “Thermo process” the milk is heated at $\sim 95^{\circ}\text{C}$ for ~ 3 minutes to denature the WPs and react them with the casein micelles. A fine coagulum is obtained on acidification from which the casein-WPs are recovered by centrifugation. Alternatively, casein-WPs are recovered from heated milk by ultrafiltration (UF) or microfiltration (MF). Undressed Quarg contains $\sim 20\%$ dry matter, $\sim 12\%$ protein, $\sim 2\%$ fat, $\sim 4\%$ lactose plus lactate, and has a pH of ~ 4.6 . Germany is the principal producer of Quarg, but it is also produced widely elsewhere. Probably the principal use is in cheese-cake which may be flavored. The production of Quarg and related products was described by Kosikowski and Mistry (1997) and Schulz-Collins and Senge (2004). The types of acid-coagulated and acid-heat-coagulated cheeses and their production were described by Lucey (2011) and (Farkye 2017).

Cultured buttermilk, another product produced from skimmed milk, is an alternative to natural buttermilk, produced mainly in countries where sweet-cream butter is produced. Skimmed milk is acidified by a culture of mesophilic lactic acid bacteria (LAB) and consumed as an alternative to fresh milk. Cultured buttermilk production was described by Libudzisz and Stepaniak (2011).

4.2.3 Caseins and Caseinates

Casein represents $\sim 80\%$ of the total protein in bovine, buffalo, caprine, or ovine milk; it comprises four proteins, α_{s1} -, α_{s2} -, β - and κ -, which occur in milk as large aggregates, micelles, and which may be recovered by isoelectric precipitation at $\sim \text{pH } 4.6$, limited proteolysis, ultracentrifugation, UF or MF. The properties of the resultant products, i.e. isoelectric (acid), rennet and micellar casein, are markedly different. Less than 80% of the total protein in milk is recovered in acid or rennet casein, with the whey proteins being lost in the whey. The whey proteins in skim milk may be precipitated with the caseins following heat denaturation (e.g. $90^{\circ}\text{C} \times 10$ minutes), by acidification to $\sim \text{pH } 4.6$, or by CaCl_2 addition, to yield casein co-precipitate; however, such co-precipitate products have not been as commercially successful as the caseins. Rennet casein is manufactured by drying of the insoluble casein fraction generated during renneting. Although very insoluble, some properties of rennet casein make it suitable for certain food applications, such as the manufacture of analogue cheese, where rennet casein is dispersed in a hot solution of calcium-binding salts before cooling to induce matrix formation (Ennis and Mulvihill 1999; O’Sullivan and Mulvihill 2001). Acid casein is produced from skim milk by isoelectric precipitation of the casein fraction at pH 4.6, typically using hydrochloric acid. The resultant curd is recovered using mechanical separation, washed and dried to produce a powder ingredient. Acid casein is completely insoluble in water, and as a result has a very limited range of applications. It can be used for nutritional supplementation of food products where solubility in water is not a requirement (e.g. protein bars and breakfast cereal).

Acid casein is normally converted to the soluble caseinate forms, for use in a wider range of food applications, by dispersion in water and adjusting the pH to ~ 6.7 with alkali, usually NaOH, to yield sodium caseinate. KOH, NH_4OH or $\text{Ca}(\text{OH})_2$ may also be used, giving the corresponding caseinate (Mulvihill and Ennis 2003). In the laboratory, caseinates may be freeze-dried but are usually spray-dried, and to a much lesser extent roller dried, in industrial-scale production. The casein present in rehydrated caseinates is

not micellar, as in milk, MPCs or micellar casein concentrates (MCCs), which results in caseinates having markedly different functional attributes such as poor wettability, high viscosity, excellent heat stability and an ability to remain stable in ethanol solutions.

The major areas of application for casein and caseinate ingredients are food and beverage, industrial, pharmaceuticals and cosmetics, with the food and beverage segment accounting for >70% of the global casein and caseinate market, growing at a rate of 5.0% p.a. (Buyer 2016). The majority of caseinate used commercially in food and beverage applications is sodium caseinate. Casein (probably acid casein) was used as a glue in ancient Egypt, Greece, Rome and China (Soutward 1989). As with many other naturally-produced polymers, such as starch, caseins exhibit excellent adhesive properties, and have been used as one of the major natural adhesive ingredients for thousands of years (Guo and Wang 2016). Around 1960, the situation changed, whereby petroleum-derived products replaced casein in many of these applications as they were cheaper and more consistent. Instead, casein found new applications in the food industry which developed many new products; casein is the functional protein of choice for many food applications, which include beverages, baked goods, coffee creamers, cheese, ice creams, whipped toppings, fudge, meat products, high-fat powders, shortenings, spreads, and nutritional products. The production, composition and functionality of caseins and caseinates have been described by Mulvihill and Ennis (2003), O'Regan and Mulvihill (2011) and Carr and Golding (2016).

4.2.4 Milk Protein Concentrates

MPCs are manufactured from skim milk by ultrafiltration, with or without diafiltration, typically followed by concentration of the total solids using evaporation before spray drying. For the fractionation of milk into casein and whey streams using physical size-based separation (i.e. as opposed to acid- or rennet-induced destabilization of casein micelles), MF membranes, with pore size typically in the range 0.1–0.4 μm are used to generate a casein-rich retentate and a whey protein-containing permeate stream. The casein fraction (i.e. retentate) produced using this approach is referred to as MCC, phosphocaseinate or native micellar casein, while the whey protein fraction (i.e. permeate) is referred to as serum protein, native whey, ideal whey, or virgin whey (Pierre et al. 1992; Kelly et al. 2000; Rizvi and Brandsma 2002; Crowley et al. 2015). Compared with whey obtained as a byproduct of cheese manufacture, MF-derived whey is free of starter culture, rennet enzyme, glycomacropeptide and any colorants (e.g. annatto) that may have been added to the milk in the preceding manufacture of cheese or rennet casein. These differences in composition make this type of whey attractive for formulation of value-added dairy-based products such as protein-rich beverages and infant nutritional formulae (McCarthy et al. 2017).

In the manufacture of MPCs, the lactose: protein ratio decreases as the protein content is increased from ~35% (MPC35) to 80% (MPC80). Higher volume concentration factors during UF, combined with extensive diafiltration, can be used to produce milk protein isolate (MPI) products with a protein content >90%. High-protein MPC and MPI are used as ingredients in a wide variety of food products, ranging from traditional dairy products (e.g. cheese, yogurt) to nutritional beverage formulations (e.g. high-protein beverages for therapeutic use or formulae for lactose-intolerant infants), where their functional attributes (high solubility, contributing opacity, imparting viscosity/

mouthfeel and binding calcium phosphate) and clean label (“milk protein,” “milk protein concentrate”) are desirable.

4.2.5 Micellar Casein Concentrate

When micellar casein (with associated minerals) is separated from the serum proteins in milk, without significantly altering micellar structure, the resultant material is termed an MCC. Less than 10% of the protein (usually 5%) in MCCs is whey protein; however, there is no standard of identity for MCCs and the distinction between MCCs and MPCs is not definitive. The production of MCC involves the use of MF membranes with wider pores than the UF membranes typically used to produce MPCs. The MF process allows whey proteins to be removed in the permeate, along with lactose and other soluble components (Pouliot et al. 1996). Diafiltration with water facilitates further removal of these components, although a certain proportion (~5%) of the whey proteins remains in the retentate with the micellar fraction. The factor which limits whey protein removal may be the progressive growth of a fouling layer comprised of casein micelles, which increases the rejection of whey proteins by a combination of electrostatic and steric repulsion during MF processing (Gésan Guiziou et al. 2013).

When MF is performed at <15 °C, β -casein is depleted from the MCC, with the degree of depletion increasing as temperature is reduced (Crowley et al. 2015). MCC is a useful material for studying casein micelles in their native state and has been used as a model system to study properties relating to the physicochemical aspects of casein micelles (Famelart et al. 1999) and casein micelle structure (Salami et al. 2013; Gonzalez-Jordan et al. 2015). MCCs are also used in sports, clinical, and medical nutrition products and facilitate the development of “slow release” protein formulations for such applications. In addition, MCCs have been used in traditional dairy products such as yogurt and cheese in increasing protein content (Karam et al. 2012), and to encapsulate bioactive substances which are hydrophobic or hydrophilic (Yazdi et al. 2014). Regular MCCs and β -casein-depleted MCCs are major co-products of ideal/native whey and β -casein, respectively, produced by membrane filtration (Crowley et al. 2015). Another active area of application-based research for MCCs is their use as semen-extenders, where they act to preserve the fertility of animal sperm during storage (Batellier et al. 1998; Bergeron et al. 2007). Some researchers have proposed the use of MCCs in liquid concentrates, in gel (Amelia and Barbano 2013) or frozen (Lu et al. 2015) form, which may allow circumvention of issues related to the poor rehydration properties of MCC powders. Compared to MPCs, MCCs are in their infancy and have not yet attracted significant commercial interest from the food industry.

4.3 Whey and Whey-Based Products

4.3.1 Introduction

Whey is an aqueous solution containing about 50% of the original nutrients present in milk, such as milk sugar (lactose), serum protein (whey proteins), minerals and all the water-soluble minor components, such as vitamins. In accordance with its origin and processing, whey can be classified as acid whey (acidification), rennet whey (enzymatic

coagulation), cheese whey (enzymatic/acidification) and ideal/native whey (MF). Sweet whey refers to cheese and rennet whey from cheese and rennet casein production, respectively, and acid whey is generated from acid casein manufacture (Bansal and Bhandari (2016). The composition of acid and rennet (sweet) whey differs markedly (Table 4.2). The global production of whey is reported to be ~180–190 million tonnes per year (Mollea et al. (2013), the majority of which is sweet whey, with whey being processed into a wide range of different products (Figure 4.3).

As the largest volume byproduct of the dairy industry, whey represents a disposal/conversion challenge, mainly due to its high lactose content, which is largely responsible for the biochemical oxygen demand (BOD) (30000–50 000 ppm) and its chemical oxygen demand (COD) (50000–80 000 ppm) (Ortega-Requena and Rebouillat 2015). The attitude toward whey and its utilization has changed over the years from being a waste material, to be treated as cheaply as possible (e.g. as pig feed, irrigated on land or dumped into waterways) to a byproduct and currently a value-added raw material. Nowadays, environmental considerations and new technologies make it technologically possible and economically viable to produce a wide range of valuable products from whey (Figure 4.3) with several applications in food, either as functional ingredients or nutritional supplements, and in pharmaceutical applications (Figure 4.4). Whey ingredients

Table 4.2 Typical composition sweet and acid whey (% by weight).

Component	Sweet whey	Acid whey
Fat ^a	0.05	0.03
Lactose ^a	5.0	4.7
Casein ^a	0.10	0.0
Whey protein ^a	0.65	0.57
True protein ^b	0.60	0.60
NPN (non-protein nitrogen) ^b	0.20	0.20
Minerals ^a	0.50	0.80
Calcium ^b	0.035	0.12
Phosphorus ^b	0.040	0.065
Sodium ^b	0.045	0.050
Potassium ^b	0.14	0.16
Chloride ^b	0.09	0.11
Minor components ^a	0.30	0.50
Water ^a	93.4	93.4
Total Solids^b	6.0	6.4
Lactic acid ^b	0.05	0.05
pH ^b	~6.0	< 5.5

^a From: Mollea et al. (2013).

^b From: Tetra Pak Processing Dairy Handbook (TetraPak 2017).

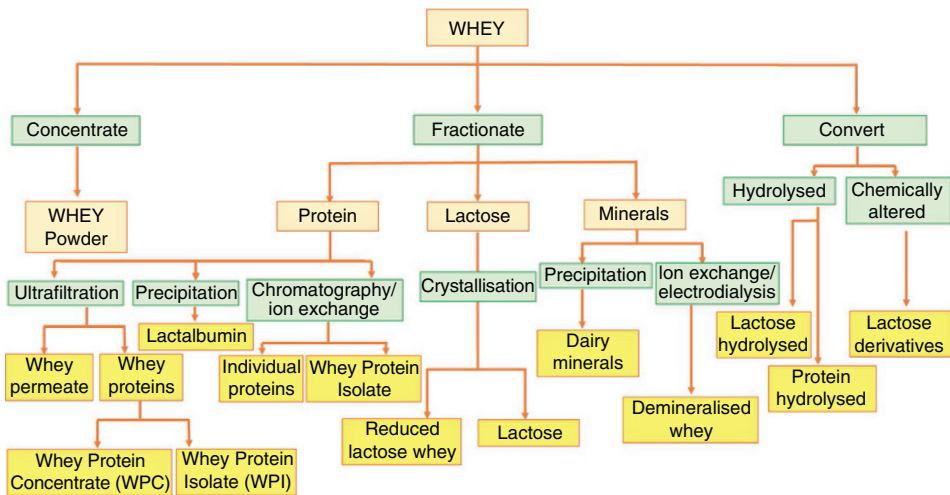


Figure 4.3 Overviewing of processing options for whey and whey products. *Source:* From: Wisconsin Centre for Dairy Research, University of Wisconsin.

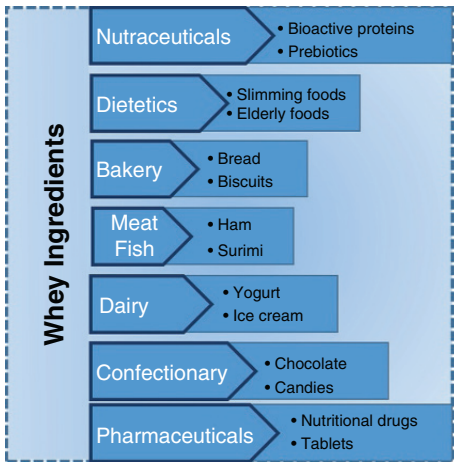


Figure 4.4 Industrial applications of whey ingredients. *Source:* Adapted from Ramos et al. (2016).

represent the fastest growing sub category of the dairy ingredients market (Markets (2016), with the market valued at \$45.55 billion in 2015 and projections to reach \$66.11 billion by 2022.

4.3.2 Cheese Whey

In 2011, the world production of cheese was approximately 17 million tonnes annually, which equates to an estimated 157 million tonnes of whey (Paterson 2011). Cheese may be produced through the use of enzymes, which coagulate casein, generating sweet whey or by adding acid (e.g. glucono-δ-lactone, lactic, sulfuric, phosphoric, hydrochloric and

citric) to lower the pH of milk and precipitate the casein, generating acid whey. Sweet whey contains caseino-macropptides (CMP), produced from κ -casein by rennet action. CMP represents ~20% of the total protein in sweet whey and it is not present in acid whey unless rennet is used in the coagulation process. Cheese varieties from which sweet whey is generated include Cheddar, Mozzarella/Pizza, Swiss and Dutch. Acid whey has a higher level of calcium than sweet whey (Table 4.2); calcium phosphate is more soluble at lower pH; therefore, the lower pH of acid whey will draw more calcium from the cheese curd into the whey than sweet whey. Cheese varieties from which acid whey is generated include Cottage, Ricotta, Quark and cream cheese (Smith 2008). During cheese making, annatto is often added to cheese-milk to confer a yellow/orange color to cheese; however, residual annatto in whey protein ingredients is undesirable in many applications (Kang et al. 2010), with a clear and colorless whey ingredient usually preferred. In addition, there are strict regulatory limits on the concentrations of norbixin, the principal carotenoid in annatto, in ingredients destined for application in infant formulae (Campbell et al. 2014), while the presence of bleaching agents (e.g. benzoyl peroxide or hydrogen peroxide) in whey-based ingredients intended for use in infant formula is also strictly regulated. These regulatory hurdles are accelerating efforts to reduce carry-over of colorant and/or bleach residues into whey intended for use in manufacture of premium nutritional ingredients. These considerations have intensified research into the use of alternative colorants in cheese making such as β -carotene, which is naturally present in milk (Moeller et al. 2014), novel colorant ingredients which associate with the casein protein-based cheese matrix and are not carried over into the whey stream (e.g. ClearWhey from Cybercolors, Cork, Ireland and Whitewhey™ from Chr Hansen, Copenhagen, Denmark, respectively), and approaches involving the production of cheese from MF retentates of milk, whereby the native/ideal whey is physically removed upstream of cheese making.

From a valorization point of view, two different options for utilization of cheese whey can be considered: the first one is based on the application of technologies to recover valuable components such as proteins and lactose (Mollea et al. 2013), which is the subject of the next several sections. The second option relies on the application of fermentation processes to obtain value-added products (Prazeres et al. 2012) such as organic acids (e.g. lactic, succinic, and propionic), single cell proteins and oils, biopolymers (enzymes, polyhydroxyalkanoates, exopolysaccharides), and bacteriocins, some of which are discussed in later sections of this chapter.

4.3.3 Whey Cream and Whey Butter

Whey cream, a byproduct generated from the processing of whey, is physically removed from fresh whey, by centrifugal separation, to reduce the fat content of whey protein-based products and to improve the efficiency of protein enrichment processes from whey (e.g. ultrafiltration). Whey cream has a similar composition to that of sweet cream, but higher levels of unsaturated fat, biologically active phospholipids (e.g. sphingomyelin) and proteins (e.g. mucins), with the latter components originating from the milk fat globule membrane (MFGM). Therefore, whey cream has the potential as a starting material for the production of bioactive lipid-rich ingredients with interesting nutritional and technological functionalities. Whey butter, which is produced by churning whey cream, has been gaining attention from the dairy industry due to the large volumes of whey and

whey cream produced by the cheese manufacturing industry (Jinjarak et al. 2006). There are currently very few economically attractive uses for this co-product, and it is generally absorbed by the mainstream butter industry, with substantial quantities being converted into butter oil. Any research contributing to better valorization of this product would be of value to butter manufacturers. From the production of whey butter, whey buttermilk (WBM) is generated as a byproduct. Sodini et al. (2006) refers to WBM as a potentially novel ingredient, with better emulsifying properties and lower foaming ability, along with good levels of protein solubility, viscosity, and emulsifying capacity over a pH range of 4–6, compared with both sweet and sour buttermilk. However, WBM is more salty, sour and astringent than sweet cream buttermilk (Olabi et al. 2015).

4.3.4 Whey Powder

Whey powder is a commodity dried whey product produced from fresh whey by concentration of the solids using evaporation, cooling, seeding with lactose crystals, and spray drying of the resultant material. The fresh whey is normally pre-treated using clarification to remove cheese and curd fines, separation to remove fat (i.e. whey cream) and thermization or pasteurization to inactivate residual rennet and starter culture activity (in the case of cheese and rennet whey). These pre-treatments of fresh liquid whey are generally common for the production of all whey-based ingredients. Whey powder can be difficult to dry, especially acid whey-based powder, due to the high concentration of lactose in all whey powder products, and minerals and lactic acid in the case of acid whey specifically. Crystallization of lactose before spray drying is required as the crystallized form of lactose is considerably more stable during spray drying and produces a less hygroscopic powder with improved yield and better physical stability of the dried powder product. Nanofiltration (NF) is sometimes used to pre-concentrate pre-treated liquid whey prior to evaporation as partial demineralization is achieved in addition to an increase in total solids, helping to improve drying performance of the resultant concentrate. Spray drying, with integrated fluid bed technology is generally used to dry whey powders while belt drying processes are sometimes used also. Whey powders typically contain 11–13% protein, 72–75% lactose and 8–9% minerals and have a wide range of applications in food formulations, e.g. ice-cream, bakery, and desserts due to key nutritional and physiochemical functionalities, such as high solubility, low viscosity and good heat stability.

4.3.5 Demineralized Whey

While whey powder has many applications, one of the compositional aspects which limits its use in more value-added applications is the high (8–9%) mineral content. Demineralized whey is manufactured by removing minerals from whey using one or more technologies including, ion exchange, electrodialysis and NF. Electrodialysis was first introduced for the demineralization of whey in the 1960s, selectively removing sodium and chloride ions, making possible the commercial production of whey protein-dominant infant nutritional products. Ion exchange technology was introduced more recently in the dairy industry for the demineralization of whey as it offers more flexibility to remove minerals (both mono- and divalent ions). NF is increasingly being used to pre-concentrate and partially demineralize liquid whey and many newer commercial whey demineralization plants use combinations of two or more of these technologies. Demineralized whey is an important ingredient in the infant formula industry, where there are

strict regulatory limits on the levels of individual minerals in the final product, while it is also used in other applications (e.g. ice cream, bakery, and confectionery) where the high mineral content of regular whey powder would be an issue. Demineralized whey is available with different extents of demineralization, and demineralized whey 90 (i.e. Demin 90) is the most common form, being used extensively in infant nutritional products, whereby the mineral load of regular whey powder is reduced by ~90% (i.e. from 9% to 1% in the whey powder ingredient).

4.3.6 Whey Protein-Based Products

On a commercial scale, a range of whey protein-enriched products can be prepared from pre-treated liquid whey using different approaches. WPCs are manufactured by UF or combined UF/DF of whey, followed by the concentration of the total solids, either by vacuum evaporation or NF and spray drying. The lactose: protein ratio decreases as the protein content increases from ~35% (WPC35) to 80% (WPC80). Higher protein concentration factors and degrees of diafiltration are required to achieve a higher protein content. High-protein WPCs have increased in popularity in recent years due to the proliferation of nutritional products (e.g. beverages and bars) which are often formulated to be rich in protein and low in carbohydrate. WPIs can be manufactured by membrane separation or ion exchange, in which the proteins are adsorbed on an ion exchange resin, washed free of lactose and salts, and then selectively eluted with acid or alkali. Alternatively, a combined MF/UF/DF process can be used, much like the production of a high-protein WPC except that fat is removed by MF. In such processes, UF is generally used to first concentrate the proteins in liquid whey, thereby reducing the hydraulic load on the MF step. During UF, any residual fat and phospholipid material from the liquid whey is concentrated along with the protein, but is removed subsequently by MF. A second UF step is then used to concentrate the whey further. WPIs with a protein content of 90–95% are available, and are typically used in high-end nutritional products (e.g. sports nutritional supplements). Compositional differences between WPIs produced by ion-exchange or membrane filtration are relatively small, although those produced by membrane filtration generally contain a much higher level of CMP.

The functional properties of WPCs and WPIs are very interesting and render these two types of whey protein ingredients extremely versatile and they support the formulation and development of many food products, as follows (Ramos et al. 2016):

- improve aeration in bakery and confectionary products;
- improve color and taste by interaction between proteins and lactose during thermal processing (Maillard reactions) in candy products (e.g. toffees, caramels, and cooked syrups);
- replace skim milk powder in dairy product formulations (e.g. yogurt, ice cream and milk chocolate drinks);
- improve the quality of meat and fish due to emulsifying, gelatin and hydrophilic attributes;
- develop infant formula with nutritional benefits by adjusting the formula composition to that of human milk; and
- develop dietetic foods with high satiety value – low fat and high protein content, with an excellent amino acid composition.

High-protein WPC and WPI products are key ingredients in several growth areas of the food industry, such as infant formulae, clinical nutrition and sports nutrition. These ingredients contribute the majority of the protein in low-lactose and lactose-free first-age infant formulae, which have a whey protein: casein ratio similar to human milk (i.e. 60 : 40). In clinical/sports nutrition, WPCs/WPIs are valued for their high concentrations of essential and branched-chain amino acids, and their ability to aid muscle synthesis.

4.3.6.1 Selectively-Enriched Protein Fractions

Enriched fractions of individual whey proteins are attracting increasing interest industrially and are generally prepared from pre-treated fresh liquid whey. WPCs enriched in α -lactalbumin (α -la) can be produced in two ways, (i) where α -la enrichment is achieved by concentrating α -la resulting in an increased α -la: β -lactoglobulin (β -lg) ratio or (ii) where CMP has been depleted resulting in an increased α -la level on a weight basis but an unchanged α -la: β -lg ratio. Such ingredients are of interest for use in premium infant formula and medical/therapeutic products (e.g. sleep promotion properties of α -la).

Lactoferrin and lactoperoxidase are produced from whey using ion-exchange chromatography as these proteins have very high isoelectric points and are positively charged at the natural pH of milk/whey, which allows their selective adsorption/elution from whey (and occasionally, milk) using cation exchange resins. Lactoferrin is a major protein in human milk, where it is present at a concentration approximately 10-fold higher than in bovine milk. Infant formulae supplemented with lactoferrin are sold in Asia (Tomita et al. 2009) and lactoferrin has also found application in cosmetic and health-care applications (El-Loly and Mahfouz 2011). To produce 1 kg of lactoferrin, a large volume of whey (~10 000 l) is needed (Etzel 2004) which means that the final ingredient typically commands a high price (~\$200–300/kg), which in turn limits the potential consumer-base for those formulating food products.

Osteopontin is a minor whey protein which can be enriched in whey using different combinations of MF and ion exchange. This ingredient is considered to have potential health benefits (e.g. bone mineralization) when added to infant formula.

CMP is a valuable ingredient, particularly as a dietary source for sufferers of phenylketonuria (PKU). PKU is characterized by an inability to metabolize the essential amino acid, phenylalanine, which virtually eliminates proteins as a source of amino acids in the PKU diet. Protein substitutes in PKU diets are based mostly on phenylalanine-free blends of amino acids. CMP is free of aromatic amino acids, including phenylalanine, making it a viable alternative to amino acid blends (van Calcar et al. 2009). Large-scale purification of CMP from sweet whey has been achieved, with the most successful methods employing ion exchange of whey (Etzel 1999; McMahon et al. 2006). The whey fraction generated during renneting of MCC is also enriched in CMP.

4.3.7 Lactose and Lactose Derivatives

4.3.7.1 Introduction

Lactose is the principal carbohydrate in the milk of most mammals, at a concentration which varies widely between species. As the principal solid constituent in bovine milk, representing ~35% of the total solids in normal milk, lactose is the principal constituent

in many dairy products, ranging from ~40% in WMP to >80% in demineralized whey powder. Therefore, the properties of several dairy products, especially concentrated and dehydrated products, are dominated by certain properties of lactose, especially its solubility, crystallization behavior, mutarotation properties and its propensity to Maillard browning (McSweeney and Fox 2009).

In the manufacture of cheese, whey represents 85–95% of the initial milk volume. After the removal of valuable whey proteins by UF, the remaining whey permeate can contain up to 85% lactose on a dry matter basis. The recovery of lactose from whey permeate can be not only economically advantageous (by adding value to an underutilized byproduct of whey protein manufacture), but also offers a significant contribution to environmental aspects, since lactose is largely responsible for the high BOD and COD of whey (Geiger et al. 2016). From cheese alone, 157 million tonnes of whey were produced globally in 2011, which roughly represents ~7 million tonnes of lactose. However, Paterson reported a global lactose production of only 0.89 million tonnes the same year, indicating there is a large excess of lactose potentially available as a byproduct (Paterson 2011).

The major commercial organizations in the whey and lactose ingredient industry are the leading dairy and cheese companies in the world such as Lactalis, Friesland Campina, Fonterra, Arla, Saputo, Glanbia, Murray Goulburn, DMK/Wheyco, Leprino, Agropur, Sachsenmilch, Bongrain/Armor Proteines, Sodiaal/Euroserum and Hilmar. Specialist whey and lactose ingredient companies such as Milk Specialties Global, Meggle, Milei, Volac and Carbery also play a similar important role in the global market place. The world's two largest dairy companies (Nestlé and Danone) are rarely actual producers, but they are major end users of whey and lactose ingredients, for applications such as infant formulae.

Besides the production of edible lactose (unmodified), lactose can be modified chemically, enzymatically, or microbiologically into a wide range of derivatives including galacto-oligosaccharides, lactulose, lactitol, lactobionic acid, hydrolyzed lactose, and tagatose, which have found largely *niche* markets with various uses. The chemistry and properties of lactose have been characterized thoroughly, see Fox (2009) and Fox et al. (2015b). The structure and properties of lactose, lactose-based products and their applications and approaches for derivatizing and adding value to lactose, are summarized in the following sections.

4.3.7.2 Structure and Properties of Lactose

Lactose is a disaccharide consisting of galactose and glucose, linked by a β 1–4 glycosidic bond. The hemiacetal group of the glucose moiety is potentially free (i.e. lactose is a reducing sugar) and may exist as α - or β -anomers. In contrast with other common sugars, lactose has low solubility; at 20 °C, the solubility of α -lactose is ~7 g/100 g water while the solubility of β -lactose is ~50 g/100 g water. Because of its lower solubility, the usual commercial form of lactose is α -lactose monohydrate. Although lactose has low solubility, when in solution it is difficult to crystallize, and, unless crystallization is controlled, will cause a sandy textural defect in liquid dairy products. Lactose is less sweet than the other common sugars, which limits its value as a sweetener, the principal use of sugars, but is beneficial for some applications for which sweetness is undesirable, e.g. as an excipient for medicinal compounds. Since lactose is a reducing sugar it can participate in the Maillard reaction with the formation of brown pigments, (off)-flavors, and a reduction in the level of lysine. The development of color and flavor is desirable in some products

(e.g. to enhance color and flavor development in bakery products), but is undesirable in others, either because of the alteration of color and flavor or because of possible reduced nutritional value due to loss of some amino acids. Caramelization (produced by heating carbohydrates above 110 °C) is generally a desirable process that produces tan to dark brown color, pleasant aromas and flavors, but can result in undesirable sensory attributes as the degree of caramelization increases (Clemens et al. 2016). For further information on the chemistry, structure, nutritional and physicochemical properties of lactose see Fox et al. (2015b).

4.3.7.3 Lactose-Based Products and their Applications

The global market for lactose is projected to exceed 1.3 million tonnes by 2022, driven by the growing popularity of dairy ingredients that improve nutrition, taste, and flavor. Attributes such as water solubility, affordability, and availability, along with its wide range of industry applications and health benefits, have also driven the increase of lactose production and consumption (Global Industry Analysts 2017). Due to its ready availability, whey is still the major source of lactose. The production of lactose essentially involves concentrating liquid whey or UF permeate of whey under vacuum, crystallization of lactose from the concentrate, recovery of the crystals by centrifugation, washing to remove other constituents and drying the crystals (Figure 4.5). The first-crop crystals are contaminated with riboflavin and are therefore yellowish; a higher grade, and hence more valuable, lactose is produced by re-dissolving and recrystallizing crude lactose. Lactose may also be recovered by precipitation with $\text{Ca}(\text{OH})_2$, especially in the presence of ethanol, methanol, or acetone (Paterson 2009, 2011). Lactose can be converted by chemical reaction, fermentation or hydrolysis into several derivatives, which are addressed in Section 4.3.7.4. The production of edible lactose was described in detail by Paterson

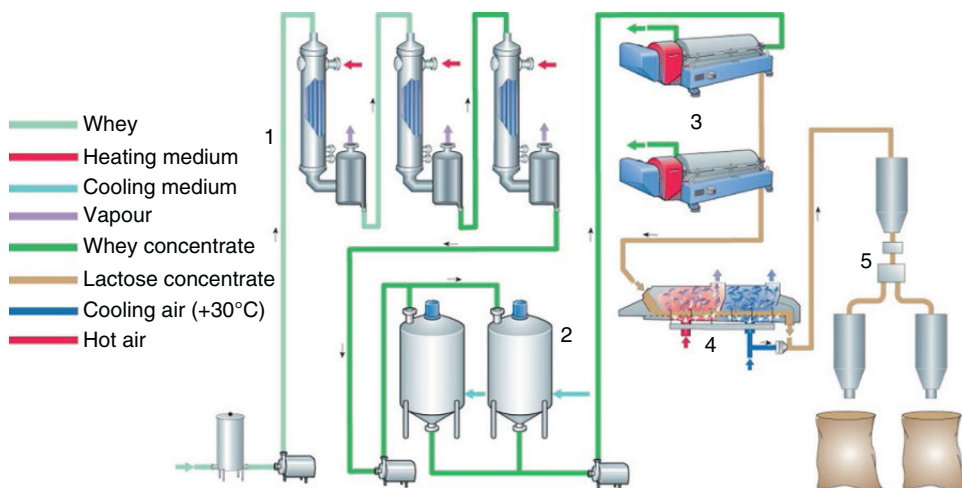


Figure 4.5 Process line for lactose manufacture. *Source:* From: Tetra Pak Processing Dairy Handbook (TetraPak 2017). 1-Evaporator; 2-Crystallization tanks; 3-Decanter centrifuges; 4-Fluid-bed dryer; 5-Packing.

(2009), who subsequently reviewed the typical challenges encountered during its production (Paterson 2011).

Lactose products are diverse and the product specificity is linear to the level of added value. The principal applications of lactose are in the food (69%) and pharmaceutical (28%) industries with minor uses in, for example, animal feed and bio-fuel production (3%). In the food industry, lactose is principally used in the processed food (including meats) sector (30%) followed by the infant formulae (18%) and confectionary (16%) sectors (Figure 4.6) (Affertsholt-Allen 2007). Lactose has a number of low-volume, speciality applications, for example, as a free-flowing or agglomerating agent, to accentuate/enhance the flavor of some foods, to improve the functionality of shortenings and as a diluent for pigments, flavors, or enzymes (O'Mahony and Fox 2014).

In bakery applications, lactose is used for its resistance to yeast fermentation and hence provides a reducing sugar for the Maillard browning reaction at the surface of baked goods, which facilitates development of a desirable brown crust. In the production of some confectionary products, it is the ability of lactose to make good quality caramel that makes it a more attractive choice than other sugars. Another reason for choosing lactose in baking and confectionary production is that it is not as sweet as sucrose and has better mouthfeel – some of the reasons why it is used extensively in chocolate manufacture. The lactose required for these and other food products needs to be of an edible standard, but does not need to be ultra-pure. This market currently uses around 780 thousand tonnes of lactose per annum (Paterson 2011). The most important application in the food sector is probably in the manufacture of humanized infant formulae based on cows' milk (human milk contains ~7% lactose compared with ~4.8% in bovine milk). The lactose used in this application can be an edible- or pharmaceutical-grade crystalline product or demineralized whey (for physiological reasons, it is necessary to reduce the concentration of inorganic salts in bovine whey) – for further information see Fox et al. (2015b).

The other main use of lactose is in the pharmaceutical industry, which requires high quality, extra-pure lactose, and therefore is more expensive, where it is used as an excipient for making tablets and as a carrier in dry powder inhalers. Lactose has also been used for the production of bio-plastic, namely polyhydroxyalkanoate (PHA) bio-polyesters, which are a group of compostable bio-plastics of increasing significance for numerous

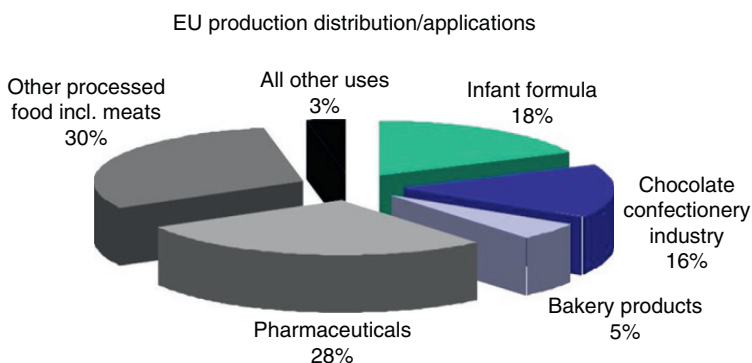


Figure 4.6 EU market structure for lactose in 2005. *Source:* From Affertsholt-Allen (2007).

industrial applications (Koller et al. 2012). The use of lactose for plastic production was addressed by Ghaffar et al. (2014) and Watanabe et al. (2014).

4.3.7.4 Approaches for Derivatizing and Adding Value to Lactose

Although the demand for lactose has been strong in recent years, it is unlikely that a profitable market exists for all the lactose potentially available from whey. For many years, the most promising idea for converting or adding value to lactose was considered to be hydrolysis to glucose and galactose. Currently, much UF permeate is converted into whey permeate powder and sold as a commodity product, but other modifications are attracting increasing attention (Paterson 2011). Derivatives can be obtained from lactose by chemical, enzymatic, or microbial modifications, including galacto-oligosaccharides, lactulose, lactitol, lactobionic acid, hydrolyzed lactose, and tagatose (Figure 4.7). The areas where current research indicates that significant amounts of lactose might be needed to meet demand are in the production of galacto-oligosaccharides (GOS) for addition to infant formulae to make them more like human milk, and in the production of tagatose, which has potential as a sugar replacer. If the price of lactose remains low, then it is possible that lactose could become an economical substrate for the production of bioethanol for use in transportation fuels or as a substrate for other fermentation products. The lactose market is growing as well as the demand for lactose specialties, which have a higher market value than the current commodity products, e.g. permeate powder and edible lactose (Figure 4.8).

4.3.7.4.1 Enzymatic

Due to the abundance of lactose in whey, one approach to increase the value of whey that has attracted increasing attention, is the bioconversion of lactose to more valuable products using β -galactosidase. The β -Galactosidases (β -Gal; EC 3.2.1.23) catalyze both the hydrolysis and transgalactosylation of β -D-galactopyranosides, including lactose and are widespread in nature. They catalyze the hydrolysis of lactose and are used in the dairy

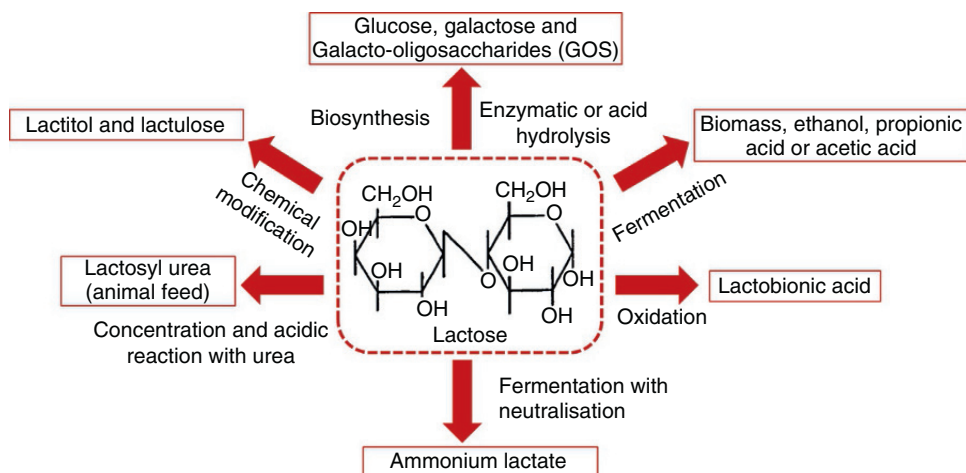


Figure 4.7 Lactose derivatives for food applications.

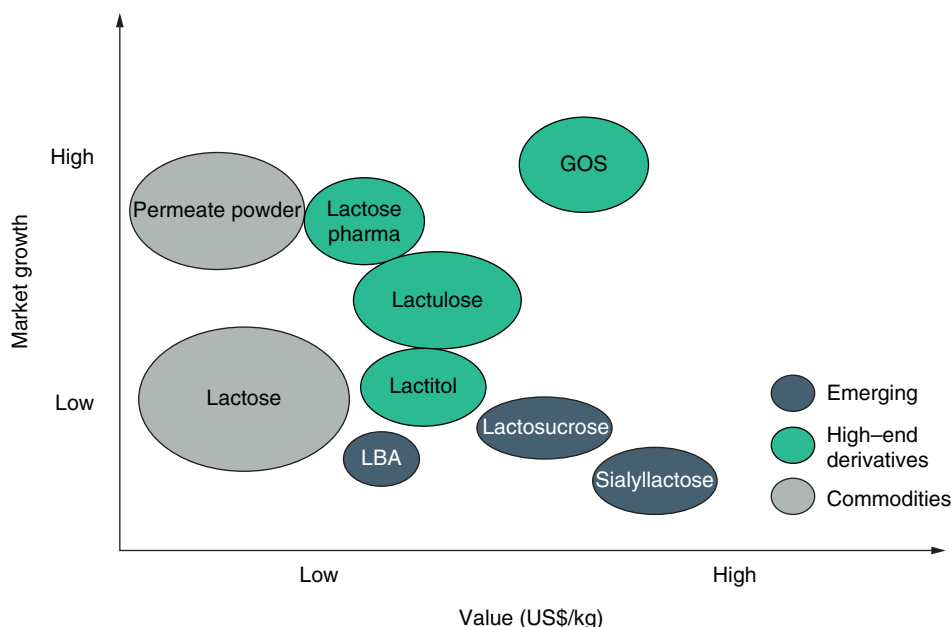


Figure 4.8 Growth opportunities for lactose and derivatives. *Source:* From Affertsholt-Allen (2007).

industry to remove lactose from various products. These enzymes also show transgalactosylation activity, which is of interest because the resulting galacto-oligosaccharides (GOS), are non-digestible carbohydrates with known prebiotic activity (Geiger et al. 2016). Commercial preparations of GOS include Vivinal[®] GOS, manufactured by Friesland Campina (The Netherlands) and Bimuno[®], from Clasado Biosciences (UK). β -Galactosidases can be obtained from various sources, including microorganisms, plants and animals and when they became commercially available, they were considered to have considerable commercial potential as a solution to the “whey problem” and for the treatment of lactose intolerance. In fact, enzymatic hydrolysis of lactose by β -galactosidase has become one of the most popular technologies to produce lactose-reduced milk and related dairy products for consumption by lactose-intolerant people (Husain 2010). An extensive list of bacterial and fungal sources of β -galactosidases, as well as the lactose conversion reaction conditions and yields of GOS, are given in the review by Torres et al. (2010). In addition, extensive literature on β -galactosidases have been reviewed by Playne and Crittenden (2009), Husain (2010), Panesar et al. (2010), Harju et al. (2012) and O’Mahony et al. (2013).

An estimated 70% of the adult human population have inadequate intestinal β -galactosidase activity and are, therefore, lactose intolerant. The problem is particularly acute among Asians and Africans and pre-hydrolysis of lactose was considered to offer the potential to develop new commercial opportunities for dairy products in those regions. Various protocols are available: addition of β -galactosidase to milk in the home, pre-treatment of milk at the factory with free or immobilized enzyme or aseptic addition of sterilized β -galactosidase to UHT milk, which appears to be particularly successful. Glucose-galactose syrups are about three times sweeter than lactose (70% as sweet as

sucrose) and hence lactose-hydrolyzed milk could be used in the production of ice cream, yogurt, or other sweetened dairy products, permitting the use of less sucrose and reducing caloric content. Why the enzymatic hydrolysis of lactose in milk is not used widely and such applications have had limited commercial success, is not clear. One possible reason is that the quality of lactose-free milk can be affected by Maillard reactions due to the presence of reducing monosaccharides, glucose, and galactose, which are significantly more reactive in Maillard reactions than lactose, causing browning, off-taste, and reduction in the nutritive value of milk protein. To avoid these problems, heat treatment of lactose-free milk should be as gentle as possible (Harju et al. 2012). Acid hydrolysis of lactose, as an alternative to the enzyme technology, does not appear practical in untreated whey due to pronounced browning and protein precipitation. Thus, it seems that the treatment of milk with β -galactosidase will be commercially successful only in *niche* markets.

4.3.7.4.2 Chemical

The lactose derivatives, lactulose, lactitol, and GOS find applications in foods and pharmaceutical preparations as prebiotics to promote gut health. Like undigested lactose, these compounds enhance the intestinal absorption of calcium and magnesium. Other lactose-derived compounds, e.g. tagatose and lactobionic acid, have potential applications as a bioactive ingredient in foods. Some of the most interesting derivatives that can be produced from lactose are summarized in brief below. For more detailed information on lactose and lactose derivatives see Schaafsma (2008) and Ganzle (2011).

4.3.7.4.2.1 Lactulose and Lactitol Lactulose (β -D-galactosyl-D-fructose) is an epimer of lactose in which the glucose moiety is isomerized to fructose. This sugar, which does not occur naturally, was first synthesized by Montgomery and Hudson (1930). Lactulose is a high added-value product of lactose and it can be produced under mild alkaline conditions via the Lobry de Bruyn-Alberda van Ekenstein reaction and at a low yield as a byproduct of β -galactosidase action on lactose. It is produced on heating milk under sterilizing conditions and is a commonly used index of the severity of the heat treatment to which milk has been subjected, e.g. to differentiate in-container sterilized milk from UHT milk; it is not present in raw or HTST pasteurized milk. Lactulose is not hydrolyzed by intestinal β -galactosidase and hence reaches the large intestine where it can be metabolized by LAB, including *Bifidobacterium* spp., acting as a prebiotic carbohydrate, which stimulates the growth of health-promoting bacteria in the gastrointestinal tract and inhibits the growth of pathogenic bacteria such as *Salmonella*. Lactulose-derived oligosaccharides may form a new group of prebiotics with properties complementary to those of lactulose (Panesar and Kumari 2011). Studies have shown that supplementing preterm infants' feeds with low doses of lactulose might have positive prebiotic effects (Riskin et al. 2010). Lactulose production, purification and potential applications, both for food and pharmaceutical uses were described by Olano and Corzo (2009), Panesar and Kumari (2011) and Aït-Aïssa and Aïder (2014). Sitanggang et al. (2016) and Parekh et al. (2016) reviewed lactulose production and significance in milk and milk products.

Lactitol (β -D-galactosyl-sorbitol) is a sugar alcohol produced on reduction of lactose, usually using Raney nickel; it does not occur naturally. It can be crystallized as a mono- or di-hydrate and is not metabolized by higher animals; it is relatively sweet and hence has potential as a non-nutritive sweetener with a wide range of applications in food, namely

to lower the caloric value of products such as jams, marmalade, chocolate, and baked goods. Being non-hygroscopic, it can be used to coat moisture-sensitive foods such as candies. It is claimed that lactitol reduces the absorption of sucrose, reduces blood and liver cholesterol levels, and is anti-cariogenic – for further details please see Fox et al. (2015b). As lactitol is not digested in the small intestine and is fermented by the colonic flora it exhibits a prebiotic effect. Both lactulose and lactitol are widely used in the treatment of patients with hepatic encephalopathy (intoxication of the brain caused by failure of the liver to convert ammonia to urea) and in patients with chronic constipation. Lactitol is positioned mostly in the food sector and used as a bulking agent for sugar-free products. In 2005, 10 000 tonnes of lactitol were produced, worth \$50 million. Danisco (Denmark), Purac (the Netherlands) and Towa (Japan) are among the main producers of lactitol (Affertsholt-Allen 2007).

4.3.7.4.2.2 Lactobionic Acid Lactobionic acid (β -D-galactosyl-gluconic acid) is produced by oxidation of the free carbonyl group of lactose and it is a relatively new compound that has not yet found application in the European food market. The acid combines a sweet taste, which is very unusual for an acid, with pH-reducing effects. Its lactone crystallizes readily and it has strong mineral-complexing properties, making it suitable for applications as a food ingredient (Schaafsma 2008; Fox et al. 2015b). Lactobionic acid is resistant to digestive enzymes and will be fermented by the intestinal flora, probably exerting prebiotic effects. It is used in preservation solutions for organs (to prevent swelling) prior to transplantation, and in skin-care products (Fox et al. 2015b). Although it is seen as a potential novel food, safety assessment and more clear evidence of mechanism of action are needed, before the compound can be marketed as a food ingredient.

4.3.7.4.2.3 Lactosyl Urea Urea can serve as a cheap source of nitrogen for cattle but its use is limited because ammonia is released too quickly, leading to a toxic level of ammonia in the blood. Reaction of urea with lactose yields lactosyl urea, from which ammonia is released more slowly than from urea (Fox et al. 2015b). Lactosyl urea is produced by the nucleophilic reaction of the amine group of urea with the carbonyl functional group of lactose (first step in the Maillard reaction) and it is used as a source of nitrogen in animal feed (Croguennec et al. 2016).

4.3.7.4.2.4 Tagatose Tagatose, a derivative of galactose, is also a relatively new compound, industrially speaking. In 2005, it was approved as a food ingredient in the European Union and now has generally recognized as safe (GRAS) status. Only 20% of tagatose is digested, the remaining 80% is fermented in the colon where it exerts prebiotic effects, favoring the production of short-chain fatty acids and the growth of LAB and has little effect on blood glucose. As a low-calorie sweetener and prebiotic, tagatose can be included in a large variety of products, namely dairy, beverages, confectionary, bakery, health bars, chewing gum, and dietary supplements (Schaafsma 2008). Tagatose is nearly as sweet as sucrose and enhances the flavor contribution of other sweeteners. Tagatose is produced commercially by SweetGredients, a company formed by Arla and Nordzucker (Denmark) (Paterson 2011).

4.3.7.4.3 Fermentation

Lactose, either in dairy permeate or pure lactose solutions, is readily fermented by LAB, especially *Lactococcus* spp. (Liu et al. 2016) and *Lactobacillus* spp. (Maślanka et al. 2015), to lactic acid. Lactic acid is widely used in the production of boiled sweets, pickled foods, and as a raw material in the manufacture of important emulsifiers for the baking industry. It can be used as a food acidulant, flavoring agent (e.g. fruit drinks and desserts), preservative, restricting the growth of microorganisms (e.g. tomato sauce and mayonnaise), chelating agent (e.g. in fats and oils), gelling agent (e.g. pectin in jams), and as a coagulating agent (e.g. acidified cheese and desserts). Lactic acid may also be used as a feed-stock, in the manufacture of plastics, or converted to ammonium lactate as a source of nitrogen for animal nutrition. Lactic acid has been reviewed by Ghaffar et al. (2014).

Propionic acid (PA), produced from lactic acid by the action of *Propionibacterium* spp., has many industrial applications, mainly as a chemical intermediate in the synthesis of cellulose fiber, herbicides, perfumes, and pharmaceuticals. PA is also an important mold inhibitor, and its ammonia, calcium, sodium and potassium salts are used widely as preservatives in animal feed and human foods (Liu et al. 2015). Lactose can also be used as a substrate for *Xanthomonas campestris* in the production of xanthan gum, which has many important rheological and structural applications in dairy (e.g. cheese, cheese products, milk and cream products), bakery products, dressings, table syrups, sauces, gravies, and beverages (e.g. pulp fruit beverages), mainly due to its unique rheological behavior (e.g. mouthfeel and flavor release), stability with salts, resistance to enzymes and water binding properties (Sharma et al. 2006).

For the purpose of alcoholic fermentation, yeasts (i.e. *Saccharomyces cerevisiae*) are usually used since they have a fast fermentation capacity and tolerate high concentrations of ethanol (up to 20% v/v). Since *S. cerevisiae* cannot ferment lactose, the lactose component of whey has to be enzymatically hydrolyzed prior to the alcoholic fermentation. The hydrolysis step is not required if *Kluyveromyces* spp. (e.g. *K. marxianus* var. *marxianus* and *Kluyveromyces fragilis* var. *marxianus*) are employed for the production of bioethanol, as they have the ability to catabolize lactose (Siso 1996; Pesta et al. 2006; Guimaraes et al. 2010; Hadiyanto et al. 2014). Over the past few decades, lactose from whey permeate has been used for bioethanol production in Ireland, New Zealand, Denmark, and in the United States of America (USA) (Guimaraes et al. 2010). In 1976, Carbery Group Ltd. was one of the first Irish dairy companies to use whey permeate from cheese manufacture to produce ethanol, which is used, among other applications, in the production of alcoholic drinks such as cream liquors. Bioethanol produced in this way may also be used for industrial purposes, or as a biofuel, but in most cases is probably not cost-competitive with ethanol produced by fermentation of sucrose or chemically. Most commonly, ethanol is produced from sugar cane or sugar beet, different crops or from cellulosic resources (wooden hydrolysates, agricultural byproducts) (Božanic et al. 2014).

The mother liquor remaining from the production of lactic acid or bioethanol may be further subjected to anaerobic digestion with the production of methane, used as a fuel (Ziemiński and Frąc 2012). Several such plants are in commercial use and Europe has a leading role in the field of biogas production due to the EU policies around renewable energy and in the more specific field of biofuels, where Germany is dominant. In the context of dairy side-streams and byproduct utilization, it is important to consider that many

of the fermentation-based modifications of lactose are probably not economical because lactose is not cost-competitive with alternative fermentation substrates, especially sucrose in molasses or glucose produced from starch; however, some of the scientific advances outlined above show promise in the production of a new generation of products, including energy, from whey (Boura et al. 2017).

4.3.8 Oligosaccharides

In addition to lactose, the milk of most, probably all, species contains other free saccharides, mainly oligosaccharides (OSs), the concentration, proportions, and types of which show large interspecies differences. General reviews on milk OSs include Mehra and Kelly (2006), Urashima et al. (2013) and Oliveira et al. (2015). Among other functions, human milk oligosaccharides (HMOs) play an important role in modulating the epithelial and immune cell responses and contribute to the maturation of the immune system and in the development of the neonatal brain and cognition functions (Bode 2012; Bode et al. 2016). Because, they are not hydrolyzed by human digestive enzymes and are fermented by colonic bacteria with the production of short-chain fatty acids, CO₂ and H₂, they specifically stimulate the growth and metabolism of intestinal bifidobacteria (Ganzle 2011). Therefore, there have been increasing efforts to mimic HMOs, their structures and especially their health benefits, and considerable interest exists in the development of OS-enriched ingredients for infant nutritional applications in particular.

Given the commercial potential of OSs, several strategies have been investigated to recover, enrich and purify those naturally occurring OSs from the milk of a number of domestic species, namely cow, sheep, and goat, which contain relatively low levels of OSs, compared with human milk. See, for example Urashima et al. (2001), Zivkovic and Barile (2011), Urashima et al. (2013) and Albrecht et al. (2014). During cheese production, almost all the lactose and most of the OSs in milk are transferred into whey, thus whey-based dairy streams represent a potential source of natural milk OSs for food applications (Mehra et al. 2014). Deproteinized and delactosed whey permeate are the two most commonly used starting materials in the development of processes for the recovery of OSs from dairy streams. Some possible approaches for producing OSs similar to those found in human milk, by recovering OSs from cow's milk whey or UF permeate were discussed by Mehra and Kelly (2006) and O'Mahony and Tuohy (2013), and generally involve the application of one or more unit operations including membrane filtration (e.g. nanofiltration) and chromatography (e.g. ion-exchange) for the separation and recovery of OSs from the other principal solid constituents of whey permeate (i.e. lactose and minerals). Similarly, Oliveira et al. (2012b), described a process for the isolation of OSs from caprine whey using membrane technology. In addition to containing about 10 times as much OSs as bovine or ovine milk, the OSs from caprine milk are the most similar (structurally) to those of human milk and have been shown to have prebiotic and anti-infective properties (Oliveira et al. 2012a), offering an alternative to bovine milk-derived OSs. However, the extraction of OSs from natural dairy sources is hampered by substrate availability, variability therein and cost of extraction, and such ingredients are still not commercially available food ingredients, unlike enzymatically-produced galacto-oligosaccharides (GOS), frequently used as prebiotic ingredients in several food formulations, especially infant formula.

4.4 Buttermilk

When cream is churned as part of the butter making process, an aqueous phase called buttermilk (BM), and a fat phase (i.e. butterfat) are generated (Conway et al. 2014b). BM is the byproduct of butter manufacture, and butter produced from ripened cream is referred to as natural (conventional) BM. Initially, all, and in fact still most, butter was produced from ripened cream and probably BM was consumed as such, especially when butter making was a farm-based industry. In 2014, nearly 10 million tonnes of butter and ghee were produced globally, an increase of 163 000 tonnes (1.7%) compared with 2013. India remains the largest producer of butter and ghee, contributing 38% of the global production. The European Union was the second largest, averaging 2.31 million tonnes of butter in 2013 (OECD-FAO 2016). Assuming that butter is made from 40% fat cream, about 10^7 tonnes of BM are produced annually. Typically, 1000 kg of milk will yield over 45 kg of butter, 2–3 kg of BM powder and a little less than 100 kg of skim milk powder.

The composition of BM varies considerably depending on the butter making technology and seasonality. Typically, natural BM contains lactose (3.5–4.9%), lactic acid (0.5%), nitrogenous compounds (2.7–3.8%), fat (0.3–1.0%) and ash (0.6–0.7%); it contains proteins and phospholipids derived from the MFGM. The composition and properties of BM were described by Sodini et al. (2006) and Vanderghem et al. (2010) and the ratio of casein to whey protein in BM is similar to that of skim milk (Corredig and Dalgleish 1997). Most of the BM produced today is dried and used as a techno-functional ingredient in a wide range of food products (e.g. salad dressings, pasta sauces, chocolate, cheese, ice cream mixes, or yogurt) (Dewettinck et al. 2008; Svanborg et al. 2015; Levin et al. 2016b). A considerable amount of sweet-cream BM is blended with skimmed milk, spray-dried and used as skim milk powder (SMP) substitute or incorporated in fat filled milk powders. The remaining liquid BM, is commonly used as animal feed.

While MFGM material is present in virtually all dairy products containing milk fat, it is naturally enriched in BM (Hintze et al. 2011) as a result of the mechanical destabilization process, which disrupts the MFGM, releasing free fat as the globules coalesce. Currently, BM is the main source of MFGM-derived phospholipids and proteins and is used to produce MFGM-enriched ingredients, thereby increasing the value of BM. The number of scientific publications on the chemistry, fractionation and functionality of BM has quadrupled over the past 20 years (PubMed); the vast majority of these studies have focussed on either fractionating or concentrating various MFGM components. The separation of MFGM material from other dairy constituents, namely proteins, can be achieved by MF, which has been used successfully for the separation and fractionation of milk fat globules (Goudedranche et al. 2000). However, the presence of skim milk solids, especially casein micelles, in this byproduct, restricts the concentration of MFGM, as the MFGM particles and casein micelles are comparable in size. A possible solution to this is to selectively dissociate casein micelles, allowing casein proteins to permeate the MF membrane, along with the whey proteins, lactose, minerals, etc., thereby allowing concentration of the MFGM material in the MF retentate stream. For example, Corredig et al. (2003) used sodium citrate to disperse the casein micelles, thereby decreasing the retention of casein upon MF, which resulted in a phospholipid-enriched retentate. Morin et al. (2007a) produced buttermilk with a lower casein content employing MF, using cream washed with skim milk ultrafiltrate; washing the cream prior to churning yields buttermilk with 74%

less protein than regular buttermilk. Jukkola et al. (2016) used MF for the separation of native milk fat globules from whole milk, which allowed ~90% of milk protein to be removed from the cream prior to butter making; on manufacturing butter using this novel stream, the resulting buttermilk was naturally enriched in MFGM components and was referred to as “ideal buttermilk.”

In addition to BM (Sachdeva and Buchheim 1997; Astaire et al. 2003; Morin et al. 2007a), other byproducts have been studied as sources of MFGM material, namely whey BM (Morin et al. 2006) or butter serum (Rombaut et al. 2006a). Morin et al. (2006) showed that whey BM obtained from churning whey cream also represents a valuable source of MFGM components that can be concentrated by MF. However, the low volumes of whey cream produced, and the higher susceptibility to oxidation of whey cream, lead to limited commercial interest in this approach. Rombaut et al. (2006b) demonstrated that butter serum is a more suitable starting material in the isolation of MFGM components than BM, because of its high polar lipid content.

A number of clinical trials support the proposed health benefits of BM (Conway et al. 2013; Conway et al. 2014a) with a limited number of innovative infant nutritional products available commercially, formulated to include MFGM and/or phospholipid materials, mostly isolated from BM (Gallier et al. 2015; Cilla et al. 2016; Claumarchirant et al. 2016). Milk polar lipids could therefore be of economic value industrially after isolation and enrichment from byproducts and marketed as functional food ingredients as they have particular nutritional and functional properties. Research on the recovery and purification of dairy-derived polar lipids, mostly using buttermilk or whey-derived streams as raw material, is very active and this promises to be an interesting area of ingredient development over the next 5–10 years (see Section 4.5.3).

4.5 The Milk Fat Globule Membrane

The lipid fraction of milk is a complex matrix composed of tri- (TGs), di- (DGs), and mono-glycerides (MGs), glycolipids (GLs), cholesterol (CH), cholesterol esters (CHEs), free fatty acids (FFAs) and phospholipids (PLs) (Jensen 2002). The milk fat occurs as globules with a nonpolar lipid core composed primarily of TGs and surrounded by the MFGM which contains both phospholipids (PLs) and glycoproteins (Keenan and Mather 2006; Ortega-Requena and Rebouillat 2015) (Figure 4.9). Due to their properties, origin, structure and original function in stabilizing the fat globules in whole milk, MFGM materials are efficient and natural emulsifiers or stabilizers (Singh 2006) and are preferentially enriched in aqueous phases like skimmed milk, buttermilk and butter serum (Rombaut et al. 2006b). Therefore, cream has a polar lipids content (expressed on the basis of total lipid) lower than skimmed milk, just as butter and cheese have a lower polar lipid content than buttermilk and whey (Contarini and Povolo 2013). However, literature values on the composition of the MFGM material are highly variable due to differences in isolation, purification and analytical techniques.

The emulsifying properties of these MFGM materials are strongly dependent on their content and type of polar lipids and proteins, as well as their possible interactions. The starting material, processing, heat treatments and isolation processes have a distinct influence on the composition of MFGM isolates and, consequently, on their

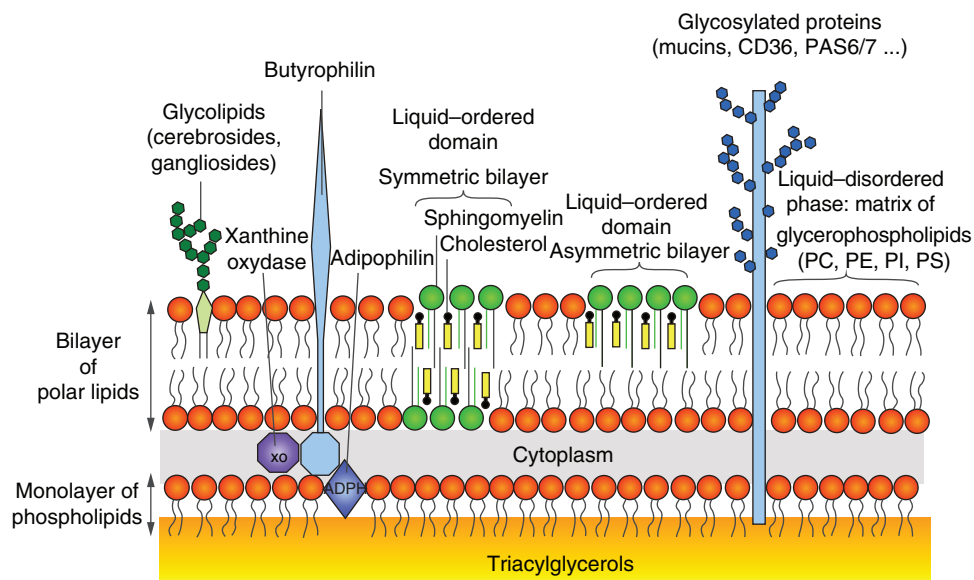


Figure 4.9 Schematic representation of the milk fat globule membrane. *Source:* From Lopez (2011). (PC-phosphatidylcholine; PE-phosphatidylethanolamine; PS-phosphatidylserine; PI-phosphatidylinositol).

technological functionalities (Phan et al. 2014). Therefore, knowledge on the origin, composition and properties of the MFGM is crucial in supporting development of new products either with improved nutritional or techno-functional properties and the composition of MFGM materials must be carefully standardized before being used in food products in order to maintain their properties. Details on the origin, nature, composition, structure, nutritional and technological properties of the MFGM were reviewed by Keenan and Mather (2006), Singh (2006) and Dewettinck et al. (2008).

4.5.1 Phospholipids of the Milk Fat Globule Membrane

Milk contains approximately 0.01–0.04% (w/w) of phospholipids (PLs), of which phosphatidylcholine (PC; 35%), phosphatidylethanolamine (PE; 30%), and sphingomyelin (SGM; 22%) together constitute 80–90%; the rest being phosphatidylserine (PS; 3%) and phosphatidylinositol (PI; 5%) (Vanderghem et al. 2010). About 60% of the total PLs are present in the MFGM and the remaining 40% in other membranous material in skim milk, which have been derived from the MFGM (Ortega-Requena and Rebouillat 2015). Phospholipids from milk, colostrum and dairy byproducts were reviewed by Conatarini and Povolo (2013) and Verardo et al. (2017).

To date, health authorities recognize only one PL component, choline, as a nutrient. Choline is a major component of PC and SGM, associated with functions such as a methyl donor and a precursor for the neurotransmitter acetylcholine. Infant formulae enriched in MFGM-derived PLs have shown promising results with respect to neurodevelopment (Timby et al. 2014) and defense against infections (Timby et al. 2015). These

health benefits are believed to be strongly associated with choline, provided by the increase of PC and SGM. In this regard, the oil droplets in infant formula enriched in MFGM material, which is still not practiced widely, would be expected to better resemble the structure of those oil droplets found in human milk (Claumarchirant et al. 2016). There has been little research on the requirements for the intake of PLs and an effective dose is very dependent on the type of PL-enriched product (Miraglio 2006). The PL content of dairy products is not only dependent of the raw material/source, but also on the choice of unit operations/processes used in their manufacture. Any treatment that disrupts the MFGM, can affect the distribution and composition of the PLs in the final matrix (Contarini and Povolito 2013).

Despite their modest concentration in the MFGM, PLs are critical in stabilizing milk fat globules against coalescence due to their mixed polar and non-polar structure, making MFGM material an efficient and natural emulsifier (Ortega-Requena and Rebouillat 2015). The use of milk PLs has been reported in a variety of foods such as frozen desserts, bakery products, pumping hams and other meats (Gerdes 2008). Le et al. (2011) used MFGM material (isolated from buttermilk) in formulating yogurts, and concluded that increasing both the polar lipid and protein content, by the addition of MFGM material, not only provided beneficial nutritional properties, but also contributed to the technological properties of the product, such as improved water-holding capacity and increased adhesiveness of the yogurt gels. Normally, the addition level of MFGM required as a technological aid (e.g. emulsifier) is lower than the addition level necessary to support a health effect; therefore, in adding MFGM material to foods to confer various health benefits (e.g. cholesterol-lowering and anti-inflammatory) it is expected that the addition levels would be in excess of that required to confer a technological benefit (Dewettinck et al. 2008; El-Loly 2011; Cilla et al. 2016). Therefore, ingredients enriched in MFGM components have the potential for use as novel food ingredients with technological and biological functionality. Good sources of MFGM-derived PLs are low-fat products such as skimmed milk (11.1–19 g PL/100 g fat), buttermilk (up to 33 g PL/100 g fat) and butter serum (14.8–48.4 g PL/100 g fat) (Pimentel et al. 2016).

4.5.2 Proteins of the Milk Fat Globule Membrane

Depending on the source, 25–70% of the MFGM, on a dry weight basis, consists of proteins (Dewettinck et al. 2008); however, the proteins of the MFGM represent only 1–4% of total milk protein. The most significant MFGM proteins are mucin 1 (MUC1), mucin 15 (MUC15), cluster of differentiation 36 (CD36), butyrophilin (BTN), lactadherin, xanthine oxidoreductase (XOR), adipophilin (ADPH), and fatty acid-binding protein (FABP), with the last three being unglycosylated. The reported composition is highly dependent on the isolation and analytical procedures used, since not all proteins are equally embedded within the matrix of the MFGM (El-Loly 2011). In the MFGM, polar lipids and proteins are closely associated so they will probably co-migrate during dairy processing; therefore, dairy products rich in polar lipids are generally also enriched in MFGM proteins (Dewettinck et al. 2008). Rombaut et al. (2006b) listed the polar lipid content (in g/100 g of product) of various dairy products during processing, butter serum has the highest amount (1.25), followed by cream (0.19), buttermilk (0.16) and skim milk has the lowest (0.02) content. Thus, it can be assumed that the MFGM proteins will follow the same general trend.

To date, important bioactivities associated with MFGM proteins include cell activity and cell growth promotion (Riccio 2004), antiviral, antimicrobial and immune-stimulating effects (Floris et al. 2010) and new-born defense mechanisms (El-Loly 2011). Mucins have been reported to have a role in the prevention of pathogen adhesion to the gut wall (Patton 2001) and lactadherin inhibits rotavirus infection (Kvistgaard et al. 2004). Since, generally, MFGM proteins are absent from infant formulae, supplementing formulae with MFGM proteins may be beneficial; however, it should be realized that specific bovine MFGM proteins, e.g. lactadherin, display less bioactivity than their human counterparts (Kvistgaard et al. 2004). MFGM proteins have been isolated and characterized by Keenan and Mather (2006) and Cavaletto et al. (2008).

4.5.3 Sources and Applications of Milk Fat Globule Membrane-Derived Ingredients

Polar lipids have been used in the food industry for a long time, in applications such as a baking improver to facilitate fat dispersion and as anti-staling agents, as additives to chocolate to reduce viscosity and prevent crystallization, as wetting enhancers for instant products, and as stabilizers for margarine to prevent spattering and browning (Van Nieuwenhuyzen 1976, 1981; Szuhaj 1983; Rombaut et al. 2004). Non-food applications, such as drug delivery vehicles, as fat liquoring for leather softening, as raw materials for the production of ceramides and liposomes (Van Nieuwenhuyzen 1981; Kisel et al. 2001; Guo et al. 2005), have been also reported.

Some milk-derived PL-enriched ingredients are commercially available, such as Lacprodan[®] PL-20 (Arla Foods Ingredients, Denmark), an MPC ingredient enriched with PL's and gangliosides, which is used, among other applications, in the formulation of infant nutritional products. Some of the benefits of this ingredient, as claimed by the manufacturer, include stability to oxidation, milky taste, and good emulsifying properties, in addition to nutritional benefits, such as its role as a source of choline, PS, and other biologically important lipids. Other examples of commercially available PL-enriched dairy-derived ingredients include the phospholipid concentrates, PC 500[™] (25% PLs), PC600[™] (75% PLs) and PC700[™] (60% PLs) (Fonterra Co-operative Group Limited, New Zealand) and SureStart[™] Lipid 100 (NZMP – Fonterra, New Zealand). The former are believed to be cream-derived ingredients, with PL concentrations more than 5000 times higher than that in raw milk, while the latter is believed to be a MFGM-based complex lipid material arising from the manufacture of AMF from cream.

MFGM materials have been recovered, enriched, and isolated from a range of dairy byproducts, such as buttermilk, butter serum, acid buttermilk, and whey, using various processes, including membrane filtration (Sachdeva and Buchheim 1997; Corredig et al. 2003; Morin et al. 2004; Rombaut et al. 2007) and thermocalcic aggregation (Rombaut and Dewettinck 2007). Rombaut and Dewettinck (2006) also described the separation of milk polar lipids from the serum phase of buttermilk by means of tangential MF and UF approaches, sometimes in combination with the stepwise addition of water (diafiltration), to facilitate further washing out of unwanted components such as lactose, whey proteins, and minerals. However, side streams and byproducts are normally subjected to several unit operations (e.g. heating, homogenization, and evaporation) in the dairy processing industry, leading to differences in composition and technological performance between different MFGM-enriched ingredients (Le et al. 2011). For example, it

has been reported that unit operations such as pasteurization, evaporation, and spray-drying affect the phospholipid content (i.e. PE, PS, and PI) of BM (Morin et al. 2007b).

Of the above byproducts, BM is the most thoroughly studied, and is often used as the starting material for the production of MFGM-enriched ingredients. However, the casein micelles in BM, which are a major solids constituent of BM, can cause difficulties as their diameter is comparable to that of MFGM fragments. Whey BM (Morin et al. 2006), the aqueous fraction obtained on churning of whey cream, and acid buttermilk whey (Rombaut et al. 2007), the aqueous fraction obtained by acidification of sweet-cream buttermilk, have received interest as feed material in the isolation of MFGM using filtration, due to the absence of casein micelles in both materials. Interestingly, Sodini et al. (2006) reported that whey BM has better emulsifying properties and a lower foaming capacity, compared to sweet or sour BM, possibly due to a higher ratio of PLs to protein in whey BM compared with either of the other two streams.

Whey protein phospholipid concentrate (WPPC), a co-product generated as a retentate stream during the MF of whey in the manufacture of WPI, is a relatively new product and does not yet have a standard of identity (Burrington et al. 2014). In 2015, the American Dairy Products Institute (ADPI) published a standard for WPPC composition: a minimum of 50% protein (dry basis), a minimum of 12% fat, a maximum of 8% ash and a maximum of 6% moisture. In 2015, whey powder (WP) remained the dominant (70%) whey product in terms of both volume and value, which together with WPC and WPI, represent a global market value of ~\$4.9 billion. In 2016, the USA alone, produced ~212 225 tonnes of WPC. The general trend in the whey ingredients market is higher growth for higher protein content products, with WPC80 and WPI having the highest growth rates between 2011 and 2015 (Affertsholt and Pedersen 2017; USDA/NASS 2017). Considering this, thousands of tonnes of WPPC are generated annually as a co-product of WPI manufacture. Like other co-products, WPPC has a variable composition, and while it is the byproduct of MF-based defatting of whey, it can be manufactured using different technology (i.e. polymeric vs ceramic MF membranes) and processing parameters; thus commercial WPPC products vary widely in terms of chemical composition, and thereby functionality (Burrington et al. 2014).

There are a number of commercially available WPPC-based products, e.g. PRO-Cream (Prinova[®], USA), Salibra[®] 700 (Glanbia Nutritionals, Ireland) and Lacprodan MFGM-10 (Arla Food Ingredients, Denmark). PRO-Cream is a co-product of WPI production and is labeled as a WPC. Lacprodan MFGM-10 is produced from a whey protein fraction with a high concentration of bioactive proteins and lipids, with the ingredient claimed to have a unique protein and lipid profile and including several bioactive compounds, such as lactoferrin, IgG, sialic acid, phospholipids and gangliosides. In addition, Salibra 700 is a value-added WPC ingredient with more than 20% bioactive components derived from whey such as glycomacropeptide (13%), immunoglobulins (5%), lactoferrin (1%) and phospholipids (2%) and can be used in food systems such as yogurt, ice cream, low-fat products, nutritional bars, frozen whipped toppings and nutritional beverages for emulsification, thickening, water-binding and texture stabilization. In addition, blends of WPPC and delactosed permeate (DLP), a byproduct of lactose manufacture, have been used in several food formulations to replace other dairy ingredients, emulsifiers, salt, and eggs in food applications such as ice cream, soups and confectionery products (Bund and Hartel 2013; Levin et al. 2016b). DLP and WPPC have been used in combination as a total replacement for eggs, in cakes, with no change in yield, color, or texture (Levin et al. 2016b).

Lecithin is a food ingredient which is naturally enriched in PLs and is normally derived as a byproduct of vegetable oil (soybean primarily) processing, or from eggs. Lecithin has many technological (e.g. viscosity modifier and emulsifier) (Szuhaj 2003) and nutritional functionalities (e.g. role in neurological development and inflammatory process) (Küllenberg et al. 2012). It may be possible to use some of the dairy-derived PL-enriched ingredients outlined earlier to replace lecithin in certain food applications, thereby adding value to an existing byproduct of the dairy industry (Zhu and Damodaran 2013). In addition, MFGM is also a natural source of antioxidants, such as vitamin E (Jensen and Nielsen 1996) and riboflavin (Kuchta et al. 2012). Therefore, if MFGM, or its components, could be isolated in greater quantities from additional dairy byproducts, such as whey BM or WPPC, in an industrially and commercially viable way, it has major potential for use as a functional food ingredient in several applications. Further research should focus on the impact of the various processes currently used for MFGM isolation and separation and how changes to the structure of MFGM material/fragments affect their nutritional and functional properties.

4.6 Milk and Whey Permeates

4.6.1 Introduction

In dairy processing, the term permeate is used to describe the fraction of milk or its derived streams which can permeate through the selectively-permeable membranes used for fractionation, enrichment or purification of target nutrients using pressure-driven membrane filtration processing. The membranes used may be of MF, UF, NF, or reverse osmosis (RO) construction/configuration and the feed material may be milk (usually pasteurized, skimmed milk) or pre-treated (clarified, separated, and pasteurized) whey, thus giving rise to a broad matrix of possible permeate streams. However, the largest by volume, and commercially most significant, permeate streams/products are whey permeate and milk permeate derived using UF membrane technology; these milk and whey permeates are obtained by UF of skim milk and pre-treated liquid whey, respectively.

Permeate is predominantly (>93%) water and contains the low molecular weight water-soluble components (i.e. lactose, minerals, vitamins, non-protein nitrogen) of milk or whey. The UF membranes used for the production of milk and whey permeate generally have a molecular weight cut-off of 5–10 kDa and are intended to retain all the milk/whey proteins in the retentate stream. Fat is also retained by such membranes but the fat content of the feed material (i.e. skim milk or pre-treated whey) is generally maintained low (<0.1%) by the use of centrifugal separation of fat in a pre-treatment step so as to minimize the fat content of the retentate and to minimize fat-based fouling of the membrane filters. MF, NF, and RO permeates of milk and whey are growing in prevalence and commercial significance as part of fractionation (e.g. separation of casein micelles and whey proteins in their native state in skim milk using MF), demineralization (e.g. removal of monovalent ions from whey in the production of demineralized whey) and pre-concentration (e.g. pre-concentration of skim milk prior to evaporation and spray drying) processes, but generally do not contribute directly to the generation of byproducts and therefore they will not be discussed further in this chapter.

4.6.2 Milk Permeate

Compared with whey permeate, milk permeate is a relatively new byproduct in the processing of milk. It is normally obtained as a side-stream from UF processing in the production of MPC and MPI ingredients, on-farm concentration of milk and in the pre-concentration of milk intended for cheesemaking. Milk permeate is considered to be a “cleaner” byproduct of milk than whey permeate, as it is physically recovered from milk at an earlier stage in processing and is free from various additives such as, rennet enzyme, pH adjusting aids, color (e.g. annatto) or starter cultures which are commonly used in the production of cheese and casein ingredients (some of which are present in the resultant whey permeate stream). Milk permeate is used mostly in liquid format (normally concentrated from its natural ~6% total solids to 20–25% total solids) for standardizing the protein content of milk powders made from a seasonal milk supply (e.g. in Ireland, the Netherlands and New Zealand), can be dried to produce milk permeate powder. It is also technologically possible to recover lactose from milk permeate, generate a range of lactose derivatives and milk minerals using the approaches outlined above, for the processing of whey permeate; however, this is not usually practiced commercially.

4.6.3 Whey Permeate

Whey permeate, as a byproduct of whey processing, has been a dairy processing side stream since the introduction of UF technology in the 1960s for the removal and concentration of proteins from whey. This UF technology-based removal of protein from whey was performed in the early days to reduce the nutrient density and associated BOD/COD of whey being discharged into waterways, but was quickly adopted for the development of WPC ingredients (Section 4.3.6). Whey permeate is now a byproduct of the production of WPC, WPI and some whey protein fractions. The typical composition of whey permeate is 93% water, 6% total solids and 0.6% protein. The volumes of whey permeate generated in the production of WPC and WPI ingredients are relatively large, especially in the production of high protein content WPC/WPI ingredients, particularly with the addition of water to the feed stream, in diafiltration, to wash out more non-protein constituents (lactose and minerals) of whey in the production of such high protein content WPC/WPI ingredients. Whey permeate can be dried to produce whey permeate powder or further processed and fractionated using a number of different approaches to yield various more value-added ingredients as summarized briefly in the following sections:

4.6.3.1 Whey Permeate Powder

Whey permeate can be evaporated and dried to produce whey permeate powder. According to the American Dairy Products Institute (ADPI), this byproduct of milk/whey has approximately 3–4% moisture, 76–85% lactose, 8–11% ash and 2–7% protein, and is sometimes referred to as deproteinized whey powder since the whey proteins are removed using UF technology during processing and the nitrogen is predominantly non-protein nitrogen. Due to the high lactose content of the resultant powders, the lactose is normally pre-crystallized (by controlled cooling, seeding and holding) post evaporation and prior to drying to help reduce lactose glass-mediated stickiness during drying and caking, crystallization, clumping of the finished product powders. Research and

development on innovative approaches to the concentration and drying of whey (and milk) permeate is currently very active with a focus on reducing stickiness during drying, increasing the capacity of drying plants and improving the stability of the resultant permeate powders (Tanguy et al. 2017).

4.6.3.2 Lactose

Whey permeate may be evaporated, typically to 60–65% total solids by vacuum evaporation at 70–75 °C and the lactose crystallized by controlled cooling, seeding and agitated storage of the mixture. The recovered (using decanter centrifuge technology usually) lactose crystals are then washed to remove impurities (i.e. minerals and vitamins), dried using fluidized bed drying technology and optionally milled to produce lactose powders of the desired particle size, density, and bulk handling properties for use as an edible ingredient in a range of food applications. The main applications of lactose are in chocolate, confectionery, and in infant formula, and increasingly in the standardization of milk powders (e.g. protein-standardized SMP). Lactose may also be further converted biochemically into a range of commercially important products as described in Sections 4.3.7.3 and 4.3.7.4.

4.6.3.3 Delactosed Permeate

DLP, also referred to as mother liquor, is the side-stream remaining after the physical removal of lactose crystals from concentrated, crystallized whey permeate. It has a substantial concentration of lactose (typically 50–55%) and is enriched in minerals (due to partial removal of lactose by crystallization), compared with regular whey permeate. For each kilogram of milk used for cheese production, close to 0.5 kg of DLP is produced (Bund and Hartel 2013). DLP is currently underutilized in the food industry, with the principal application being as a binder (with some nutritional contribution) in the production of pelletized animal feed products. The excess is typically spread on land, treated as an effluent or used as a feedstock in energy production using anaerobic digestion. Therefore, if DLP could be used in value-added food applications, it would greatly benefit the dairy industry in terms of reduced disposal costs and increased profitability. Development of processes for the conversion of the relatively unstable liquid format into a more stable powder format is an active area of research. DLP is very difficult to dry as the concentrate has a low glass transition temperature and the resultant powder is very hygroscopic and sticky. To the authors' knowledge, there is currently only one DLP powder product commercially available, from Leprino Foods, Denver, US.

The composition and drying properties of DLP have been studied by Liang et al. (2009) and Bund and Hartel (2010); this work showed that the composition (sugar and mineral profiles and lactic acid content), and the ability to dry different DLP materials were influenced by the source of the permeate. DLP has important functional properties that make it a useful ingredient in food applications such as ice cream, soup, and caramel (Levin et al. 2016b). Due to its mineral contribution and salty flavor, DLP (and other permeate materials) have been shown to be effective in reducing the level of sodium in formulated food products (Dixon 2008; Burrington et al. 2014; Smith et al. 2016). In these studies, it was shown that the replacement ratio for whey permeate is roughly 10 g of permeate for 1 g of NaCl, whereas only ~3 g of dry DLP is required to achieve the same sensory properties. DLP, in liquid form, has been shown to extend the shelf-life of fruits and vegetables

(Ahmed et al. 2011, 2012a,b, 2013a,b). The composition and functionality of DLP were described by Levin et al. (2016a).

4.6.3.4 Whey Minerals

Whey permeate is a rich source of dairy minerals, which are incorporated either into products such as whey permeate powder or removed in the manufacture of products such as lactose. Much of the mineral content in whey permeate (especially calcium and phosphate) may be recovered as a discrete ingredient by rendering them insoluble under certain conditions of pH and temperature and physically removing them after precipitation. The resultant material can be washed and dried to produce a powder (e.g. Tru-Cal™, Glanbia Nutritionals, USA), enriched in natural milk minerals for use as a supplement in various food applications (e.g. dairy protein beverages).

4.6.3.5 Ethanol Production

Whey, or more commonly whey permeate, as a rich liquid source of fermentable lactose, can be used for the commercial production of ethanol. This process involves the fermentation of whey permeate using lactose-metabolizing yeast to produce ethanol, which is then recovered by distillation to produce an industrial ethanol product which is used in alcoholic beverages for human consumption, cleaning/sanitation applications and bio-fuel in flexi-fuel vehicles (for further information see Section 4.3.7.4.3).

4.6.4 Developments in Dairy Permeates

Dairy permeate powders are used in a wide range of food applications and may be used to replace other dairy solids in several food applications, including, but not limited to, bakery and confectionary products. Dairy permeates may also be used in such products to replace sucrose or corn syrups, thereby reducing sugar and salt levels in these applications. Permeate can also be a source of lactose and minerals required for the formulation of nutritional products for the animal feed sector. Such is the extent of recent scientific study and commercial significance of dairy-based permeate powders that the International Dairy Federation (IDF) collaborated with Codex Alimentarius in the development and dissemination of a science-based international standard to clarify and promote the identity, composition, safety and quality of powdered dairy permeates as ingredients in food applications. A key driver of this new standard was that, from a commercial perspective, there was no commonly agreed definition of what constituted a dairy permeate powder, which hindered global harmonization of fair trade practices. The global permeate market has been growing steadily since 2012 but is expected to grow at a moderate rate (4.5%) throughout 2017–2027. This growth can be attributed to the increase in global consumption of food products in which whey permeate has been increasing, namely bakery and dairy products. The market estimation of this segment in 2017 was around \$161 million and is anticipated to reach a value of more than \$250 million by the end of 2027. However, the animal feed segment is expected to be the largest segment with a higher market value and is likely to dominate the global permeate market.

4.6.5 Separator Sludge and Microfiltration Retentates

Heat treatments are commonly applied to minimize health hazards and control bacterial growth during processing of liquid dairy streams. However, these heat treatments almost always affect the flavor and functionality of dairy products treated in this way. Centrifugation, using a bacteria-removing centrifuge, is sometimes used for the physical removal of bacteria and other unwanted contaminants (e.g. somatic cells, hair, dirt etc.) from milk and dairy streams; this process is commonly referred as bactofugation, as a result of the commercial equipment manufactured by Tetra Pak (i.e. Bactofuge™) for such applications. Due to the high microbial load and low volumes produced, this separator sludge byproduct material is normally discarded to the effluent plant.

The decimal reduction is usually low and significant loss of protein takes place with this approach. In that context, MF is increasingly being applied to remove bacteria from milk, especially skim milk, as the size range of fat globules and bacteria overlap (Gésan-Guiziou 2017). As an example, Tetra Pak have an MF-based system (Bactocatch®) available for the treatment of milk and other liquid dairy streams, which removes 99.6–99.98% of all bacteria and spores (Figure 4.10). Such technology is used, for example, in the production of extended shelf-life milk and in the removal of spore from milk intended for manufacture of cheese varieties, where it is desirable to avoid late gas blowing, caused by spore-forming bacteria. The resulting retentate byproduct stream contains valuable milk components and is normally subjected to high heat treatment and re-incorporated into the original milk stream or added to another product with less demanding quality criteria, but is generally not fed to the effluent treatment plant.

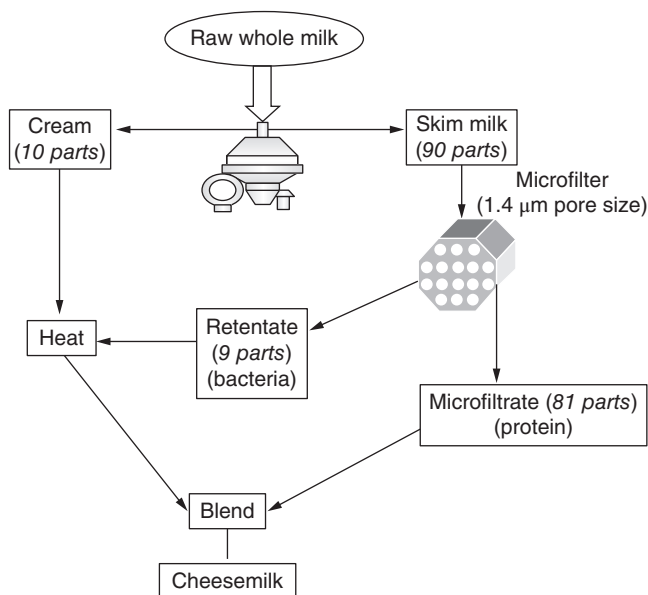


Figure 4.10 Process for removal of bacteria from milk by microfiltration. *Source:* From: (Mistry 2002).

4.7 Indigenous Milk Enzymes

The principal indigenous enzymes in milk and their catalytic activity are listed in Table 4.3. Research on the indigenous enzymes in milk dates from 1881 and a very extensive literature has accumulated, which has been reviewed, e.g. (Fox and Kelly 2006a,b) and O'Mahony et al. (2013). At least 60 indigenous enzymes have been reported in normal bovine milk. They arise from (i) the blood via defective mammary cell membranes; (ii) secretory cell cytoplasm, some of which is occasionally entrapped within fat globules by the encircling fat globule membrane (MFGM; see Section 4.5); and (iii) the MFGM itself, the outer layers of which are derived from the apical membrane of the secretory cell, which, in turn, originates from the Golgi membranes; this is probably the principal source of the indigenous enzymes in milk. Thus, most enzymes enter milk due to peculiarities of the mechanism by which milk constituents, especially the fat globules, are excreted from the secretory cells. Milk does not contain substrates for many of the enzymes present, while others are inactive in milk owing to unsuitable environmental conditions, e.g. pH.

Many indigenous milk enzymes are technologically significant from five viewpoints:

- 1) deterioration (lipase (potentially, the most significant enzyme in milk), proteinase, acid phosphatase and xanthine oxidoreductase) or preservation (sulfhydryl oxidase, superoxide dismutase) of milk quality;
- 2) as indices of the thermal history of milk: amylase, alkaline phosphatase, γ -glutamyl transferase, lactoperoxidase;

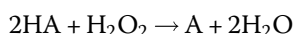
Table 4.3 Indigenous Enzymes of Significance to Milk.

Enzyme	Reaction	Importance
Lipase	Triglycerides + $H_2O \rightarrow$ fatty acids + partial glycerides + glycerol	Off flavors in milk, flavor development in Blue cheese
Proteinase (plasmin)	Hydrolysis of peptide bonds, particularly in β -casein	Reduced storage stability of UHT products; cheese ripening
Catalase	$2H_2O_2 \rightarrow O_2 + 2H_2O$	Index of mastitis; pro-oxidant
Lysozyme	Hydrolysis of mucopolysaccharides	Bacteriocidal agent
Xanthine oxidase	Aldehyde + $H_2O + O_2 \rightarrow$ Acid + H_2O_2	Pro-oxidant; cheese ripening
Sulfhydryl oxidase	$2RSH + O_2 \rightarrow RSSR + H_2O_2$	Amelioration of cooked flavor
Superoxide dismutase	$2O_2^- + 2H^+ \rightarrow H_2O_2 + O_2$	Antioxidant
Lactoperoxidase	$H_2O_2 + AH_2 \rightarrow 2H_2O + A$	Index of pasteurization; bacteriocidal agent; index of mastitis; pro-oxidant
Alkaline phosphomonoesterase	Hydrolysis of phosphoric acid esters	Index of pasteurization
Acid phosphomonoesterase	Hydrolysis of phosphoric acid esters	Reduce heat stability of milk; cheese ripening

Source: From Fox et al. (2015a).

- 3) as indices of mastitic infection: the concentration of several enzymes increases on mastitic infection, especially catalase, *N*-acetyl- β -D-glucosaminidase and acid phosphatase;
- 4) antimicrobial activity: lysozyme, lactoperoxidase (which is exploited as a component of the lactoperoxidase-thiocyanate system for the cold pasteurization of milk); and
- 5) as a potential commercial source of enzymes: e.g. ribonuclease, lactoperoxidase.

With a few exceptions (e.g. lysozyme and lactoperoxidase), the indigenous milk enzymes do not have a beneficial effect on the nutritional or organoleptic attributes of milk, and hence their inactivation by heat is one of the objectives of many dairy processes. Milk could serve as a commercial source of several enzymes, but to the best of the authors knowledge, the only commercially produced enzyme is lactoperoxidase. Peroxidases, which are widely distributed in plant, animal, and microbial tissues and secretions, catalyze the following reaction:



where HA is an oxidizable substrate or a hydrogen donor.

Work on the isolation of LPO commenced in the 1920s and LPO was isolated and crystallized in the 1940s. Since then, several improved methods for the isolation of LPO have been published and its characteristics refined. Since LPO is cationic at the pH of milk, as are lactoferrin and some other minor proteins, it can be isolated easily from milk or whey using cation exchange chromatography. There are 10 isozymes of LPO, arising from differences in the level of glycosylation and deamination of Gln or Asn. LPO is synthesized in the mammary gland and is the second most abundant enzyme in milk (next to xanthine oxidoreductase), constituting ~0.5% of the total whey proteins (~0.1% of total protein). LPO binds a Ca^{2+} , which has a major effect on its stability, including heat stability; at a pH below ~5.0, the Ca^{2+} is lost, with a consequent loss of stability. Apart from its exploitation as an index of flash or super-HTST pasteurization, LPO is technologically significant for the following reasons:

- a) It is a possible index of mastitic infection but is not well correlated with somatic cell count.
- b) LPO causes non-enzymatic oxidation of unsaturated lipids, acting through its heme group; the heat-denatured enzyme is more active than the native enzyme.
- c) Milk contains bacteriostatic or bactericidal substances referred to as lactenins, one of which is LPO, which requires H_2O_2 and thiocyanate (SCN^-) to cause inhibition. The nature, mode of action and specificity of the LPO- SCN^- - H_2O_2 system has been studied widely.

LPO and thiocyanate, which is produced in the rumen by enzymic hydrolysis of thio-glycosides from *Brassica* plants, occur naturally in milk, but H_2O_2 does not. In the presence of low levels of H_2O_2 and SCN^- , LPO exhibits very potent bactericidal activity; this system is 50–100 times more effective than H_2O_2 alone. The LPO system has good bactericidal efficiency for the cold pasteurization of fluids or sanitization of immobilized enzyme column. Indigenous xanthine oxidoreductase, acting on added hypoxanthine, may also be exploited to produce H_2O_2 . The bactericidal effects of the LPO- H_2O_2 - SCN^- system may be used to cold pasteurize milk in situations where refrigeration

and/or thermal pasteurization is lacking. Addition of isolated LPO to milk replacers for calves or piglets reduces the incidence of enteritis. Where permitted, the LPO system may also be exploited for bleaching colored whey. Milk contains high levels of lysozyme; however, egg white is the main commercial source. Lysozyme is used as alternative to nitrate, e.g. by Italian, Dutch, and Swiss cheese makers, to prevent cheese from blowing by the action of *Clostridium*.

4.8 Milk Salts

The salts of milk are mainly the phosphates, citrates, chlorides, sulfates, carbonates and bicarbonates of sodium, potassium, calcium and magnesium. Approximately 20 other elements are present in milk in trace quantities, including copper, iron, lead, boron, manganese, zinc, and iodine. There is no lactate in freshly drawn milk but may be present in stored milk and in milk products. The ash content of bovine milk remains relatively constant at 0.7–0.8%, but the relative concentrations of the various ions can vary considerably. Table 4.4, shows the average concentration of the principal ions in milk, the usual range and the extreme ranges encountered. The latter undoubtedly includes abnormal milk, e.g. colostrum, very late lactation milk or milk from cows with mastitic infection.

The concentration of ash in human milk is only ~0.2%; the concentration of all principal and several minor ions is higher in bovine than in human milk. Consumption of unmodified bovine milk by human babies causes increased renal load and hence demineralized bovine milk or whey should be used in the preparation of infant formulae. Certain of the milk salts, e.g. chlorides, and the salts of sodium and potassium are sufficiently soluble to be present almost entirely in the dissolved phase. But the concentration of others, in particular calcium phosphate, is higher than can be maintained in solution

Table 4.4 Concentration of milk salt constituents (mg L⁻¹ milk).

Constituent	Average content	Usual range	Extremes reported
Sodium	500	350–600	110–1150
Potassium	1450	1350–1550	1150–2000
Calcium	1200	1000–1400	650–2650
Magnesium	130	1000–150	20–230
Phosphorus (Total) ^a	950	750–1100	470–1440
Phosphorus (Inorganic) ^b	750		
Chloride	1000	800–1400	540–2420
Sulfate	100		
Carbonate (as CO ₂)	200		
Citrate (as citric acid)	1750		

^a Total phosphorus includes colloidal inorganic phosphate, casein (organic) phosphate soluble, inorganic phosphate, ester phosphate and phospholipids.

^b Phosphorus (inorganic) includes colloidal inorganic phosphate and soluble inorganic phosphate. From: Fox et al. (2015c).

at the normal pH of milk; consequently, these exist partly in soluble form and partly in an insoluble or colloidal form associated with casein (i.e. as an integral part of casein micelles). Milk salts chemistry, distribution, and technological significance have been reviewed by Holt (1985), Gaucheron (2005) and Lucey and Horne (2009), respectively.

All the major ionic species in milk, with the exception of Cl^- , are distributed between the soluble and colloidal phases, but the principal colloidal salt is calcium phosphate; about 67% and 57%, respectively, of the total calcium and phosphate are in the colloidal phase. The colloidal inorganic salts are, therefore, frequently referred to as colloidal calcium phosphate (CCP) although some sodium, potassium, magnesium, and citrate are also present in the colloidal phase. See Fox et al. (2015c). The distribution of salts between the colloidal and soluble phases is influenced by several factors, as summarized in Figure 4.11. The salts of milk are generally recovered as a component of dairy products such as SMP, WMP, WPC, MPC, MCC, etc. In addition to the salts recovered in these products, significant quantities of milk salts are available in low value side-streams of dairy processing, such as whey permeate.

There are a limited number of processes and products developed, and to a limited extent, commercialized, for the recovery of milk salts as ingredients in their own right. These processes normally involve the precipitation and recovery of milk salts from UF permeate of whey, although other dairy processing side-streams and byproducts can also be used as starting material. One option for preparing milk salts exploits the fact that calcium phosphate is inversely soluble with temperature, and careful control of pH,

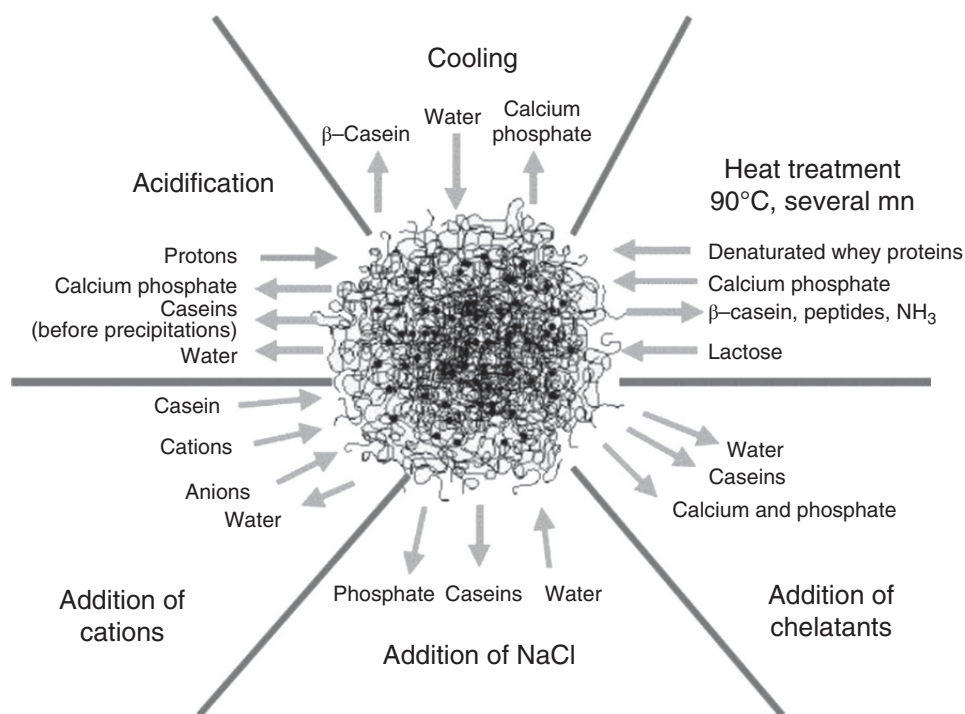


Figure 4.11 Schematic representation of the changes that occur in the distribution of salts in milk. Source: From: Fox et al. (2015c).

temperature, and time can be exploited to achieve thermocalcic precipitation of salts from dairy processing side-streams such as whey or whey permeate. This precipitated milk salts material can be physically recovered (e.g. using centrifugal technology), washed, and dried to produce powdered milk salts ingredients. Examples of commercially available, natural, milk salt-based products include TruCal® (Glanbia Nutritionals, Ireland), Valio Valsa® (Valio Foods, Finland) and Capolac® (Arla Foods Ingredients, Denmark). The principal applications of such milk salts ingredients are as substitutes for sodium chloride (for example in high-fat spreads, cheese, bread and meat products) and as a natural source of mineral supplements.

4.9 Colostrum

Colostrum, the mammary secretion during five to seven days *post-partum*, differs markedly from mature milk. The principal difference is in the concentration of immunoglobulins (Ig) which are about 10% in first bovine colostrum. The type of Ig varies with the species; the colostrum of cattle, goat, sheep and buffalo contains mainly IgG1, with lesser amounts of IgG2, IgA, and IgM. Bovine colostrum has been studied fairly thoroughly and the literature has been reviewed by McGrath et al. (2016). Human colostrum contains mainly IgA, with low levels of IgM and IgG. Ruminants do not transfer Igs to the foetus in utero and the neonate lacks Ig in its blood at birth and is very susceptible to infection. However, the neonate's intestine is permeable to large molecules for some days after birth and absorbs the colostral Ig and rapidly builds up Ig in its blood stream; it produces its own Ig after a few weeks. The modern dairy cow produces much more colostrum than its calf needs or can even consume, and milk is not supplied commercially from farms to creameries for the first several days post calving. Therefore, excess colostrum represents a byproduct of the dairy industry and a small proportion of bovine colostrum is dried and pelleted and fed to orphaned or abandoned calves; and further details on this use for colostrum can be found in O'Mahony et al. (2013). The American Dairy Products Institute has a standard on whole colostrum powder, defined as the product obtained by the drying of colostrum that comes from cows within 48 hours after giving birth. It contains fat (>17.5%), proteins (>40%), carbohydrates (<35%), vitamins and minerals and is used in several food applications such as, beverage bases, dairy product analogs, milk, milk products, nutrition bars and snacks.

Acknowledgments

The authors would like to acknowledge the Dairy Processing Technology Centre (DPTC), an Enterprise Ireland initiative, for financial support and permission to publish this work. This work was supported by the Irish State through funding from the Technology Centres Programme (Grant Number TC/2014/0016).

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